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Ueda et al.

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(45) **Date of Patent: Nov. 8, 2016**

(54) **NONRECIPROCAL TRANSMISSION LINE APPARATUS WHOSE PROPAGATION CONSTANTS IN FORWARD AND BACKWARD DIRECTIONS ARE DIFFERENT FROM EACH OTHER**

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(73) Assignee: **JAPAN SCIENCE AND TECHNOLOGY AGENCY**, Saitama (JP)

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§ 371 (c)(1),
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PCT Pub. Date: **Sep. 12, 2014**

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H01P 1/32 (2006.01)
H01P 1/19 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC . ***H01P 1/19*** (2013.01); ***H01P 1/32*** (2013.01); ***H01P 3/08*** (2013.01); ***H01Q 13/20*** (2013.01)

(58) **Field of Classification Search**
CPC H01P 1/32; H01P 3/08
USPC 333/24.1, 236, 238
See application file for complete search history.

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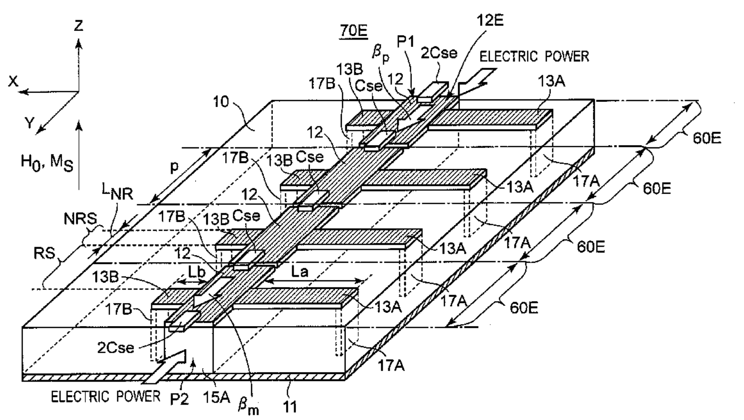
(74) *Attorney, Agent, or Firm* — Wenderoth, Lind & Ponack, L.L.P.

(57) **ABSTRACT**

When a phase constant in a first mode of propagation in the forward direction is β_p, and a phase constant in a second mode of propagation in the backward direction is β_m, respective first and second electrical lengths of stub conductors are set so that a function of nonreciprocal phase shift amount $\beta_{NR}=(\beta_p-\beta_m)/2$ with respect to an operating angular frequency comes close to a function β_{NRZ} with respect to an operating angular frequency, when beam squint of such a phenomenon that a radiation direction of electromagnetic waves radiated from a nonreciprocal transmission line apparatus changes in accordance with frequency does not occur in the vicinity of an intersection of a dispersion curve representing a relation between the phase constant β_p and the operating angular frequency and a dispersion curve representing a relation between the phase constant β_m and the operating angular frequency.

7 Claims, 28 Drawing Sheets



(51) **Int. Cl.**
H01P 3/08 (2006.01)
H01Q 13/20 (2006.01)

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Fig. 1

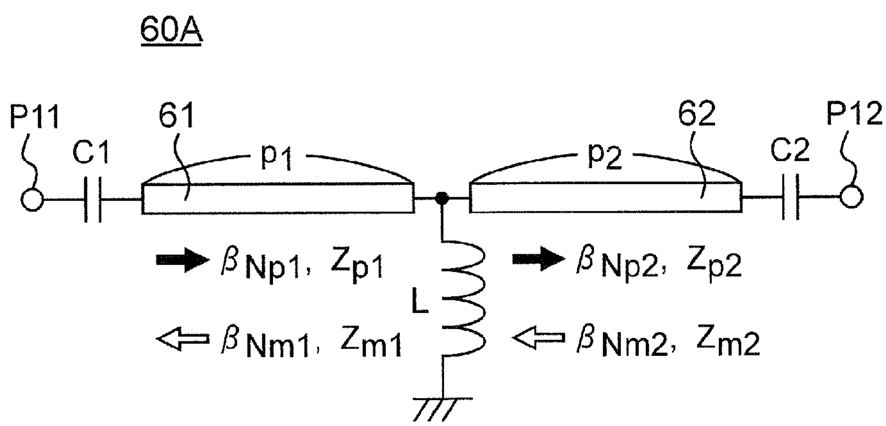


Fig. 2

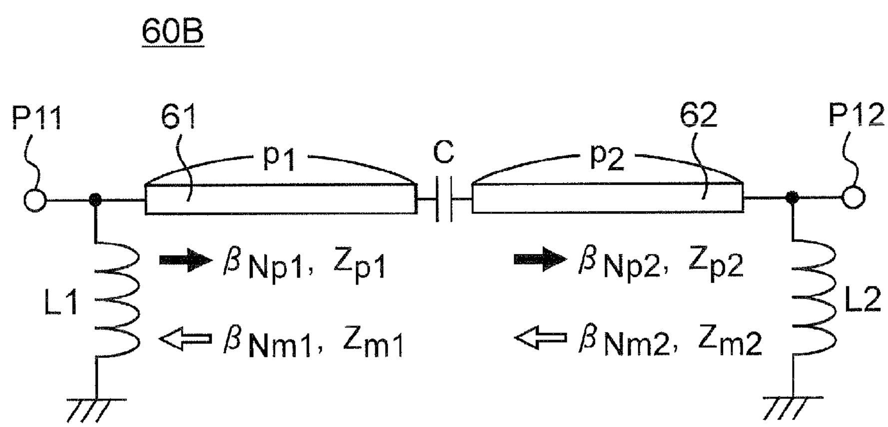
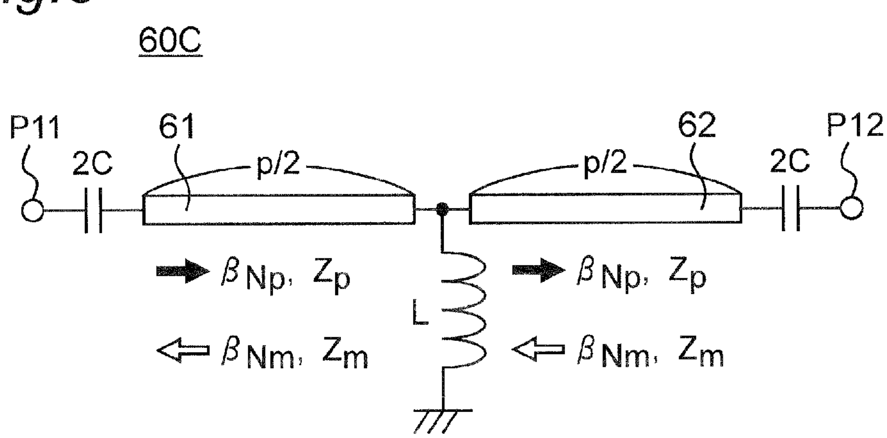


Fig. 3



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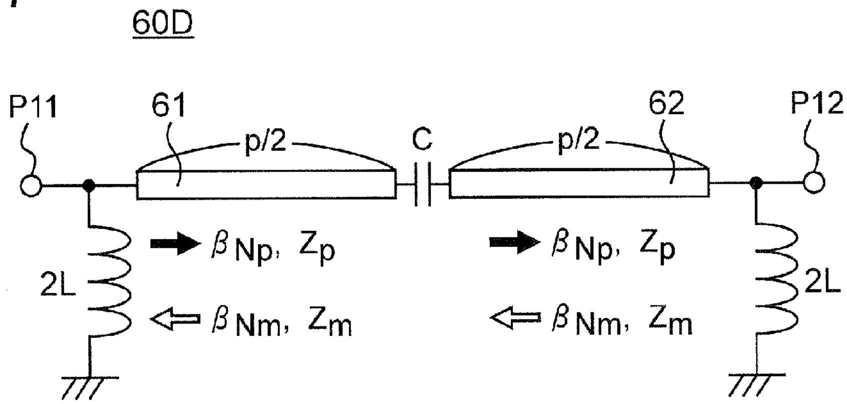


Fig.5

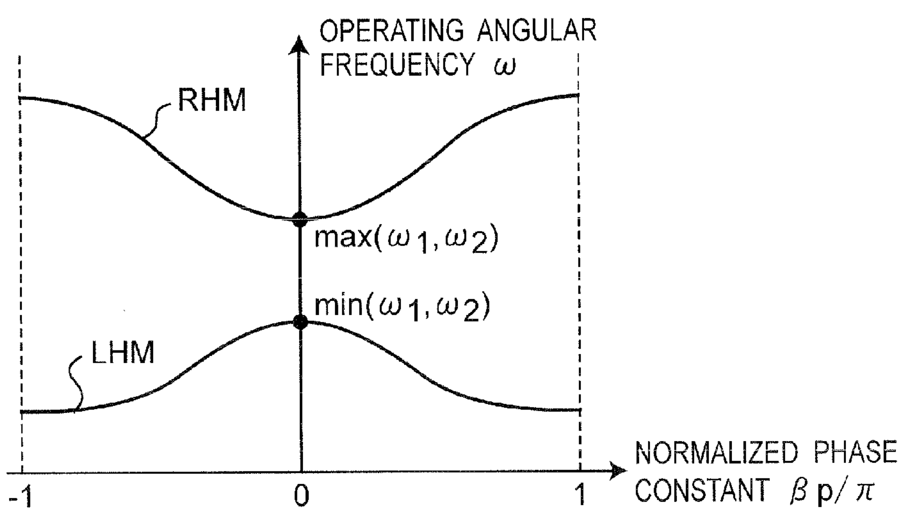


Fig.6

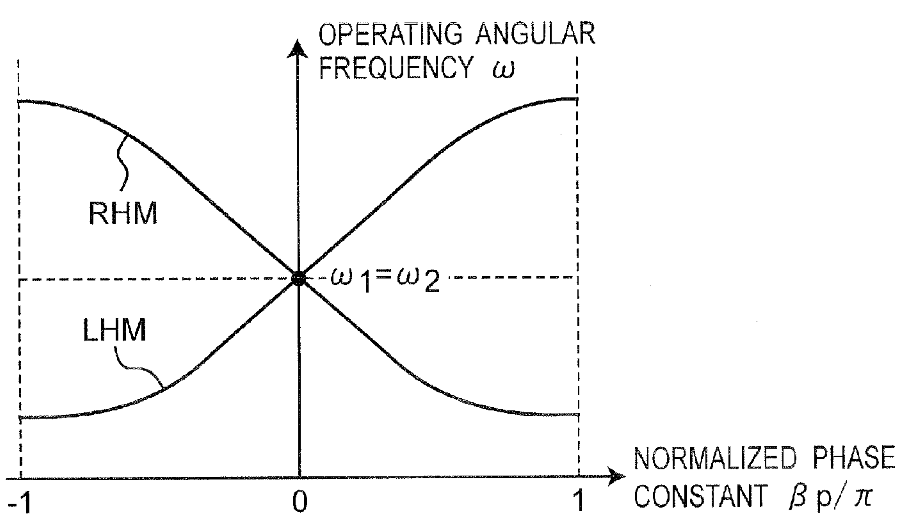


Fig.7

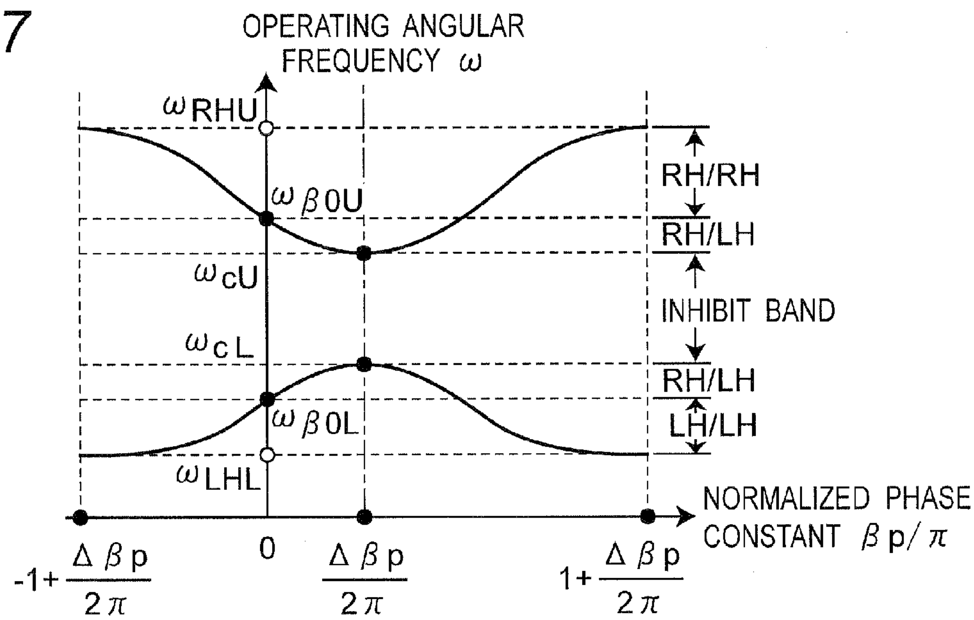


Fig.8

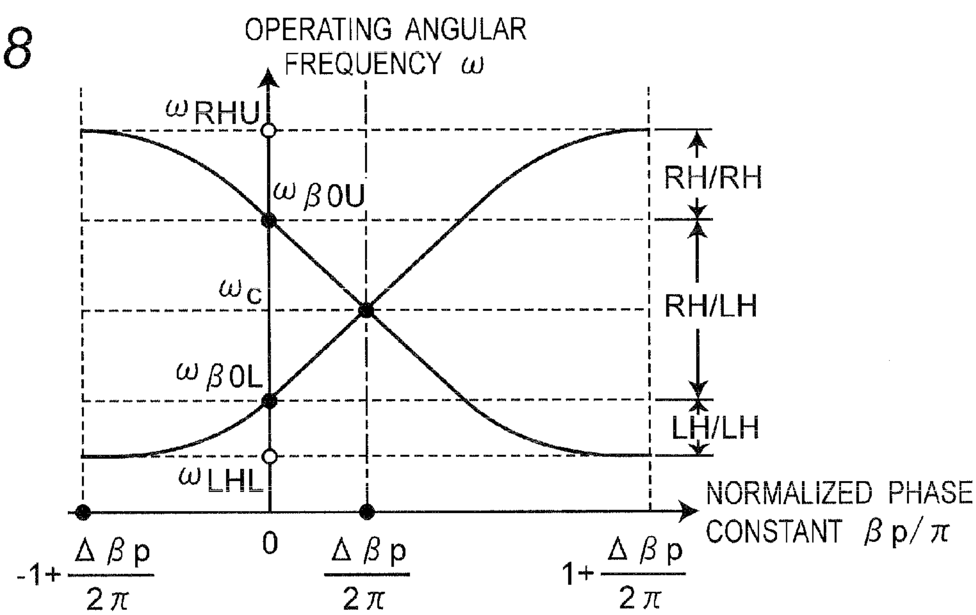


Fig.9

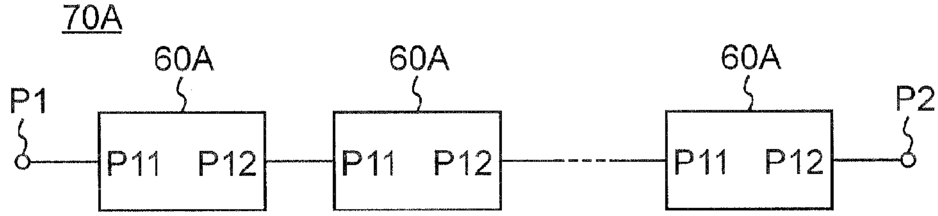
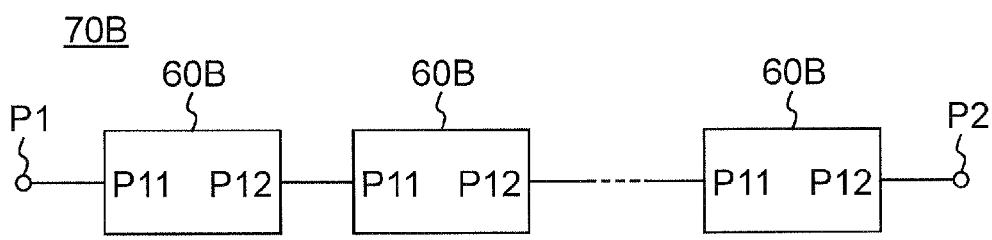


Fig.10



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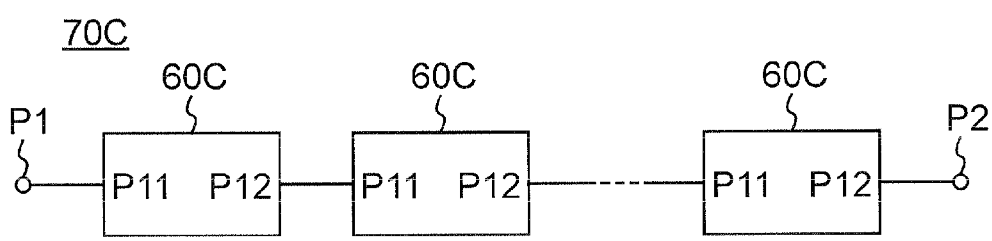


Fig.12

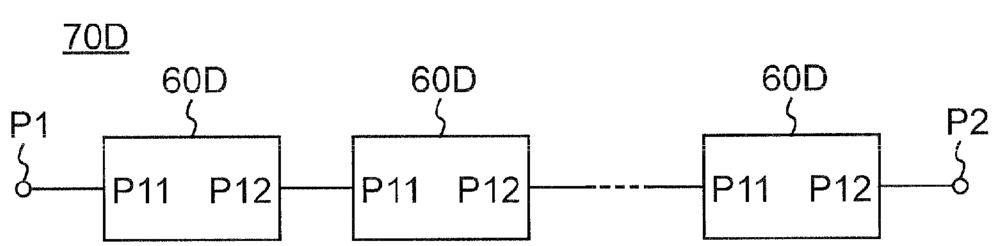
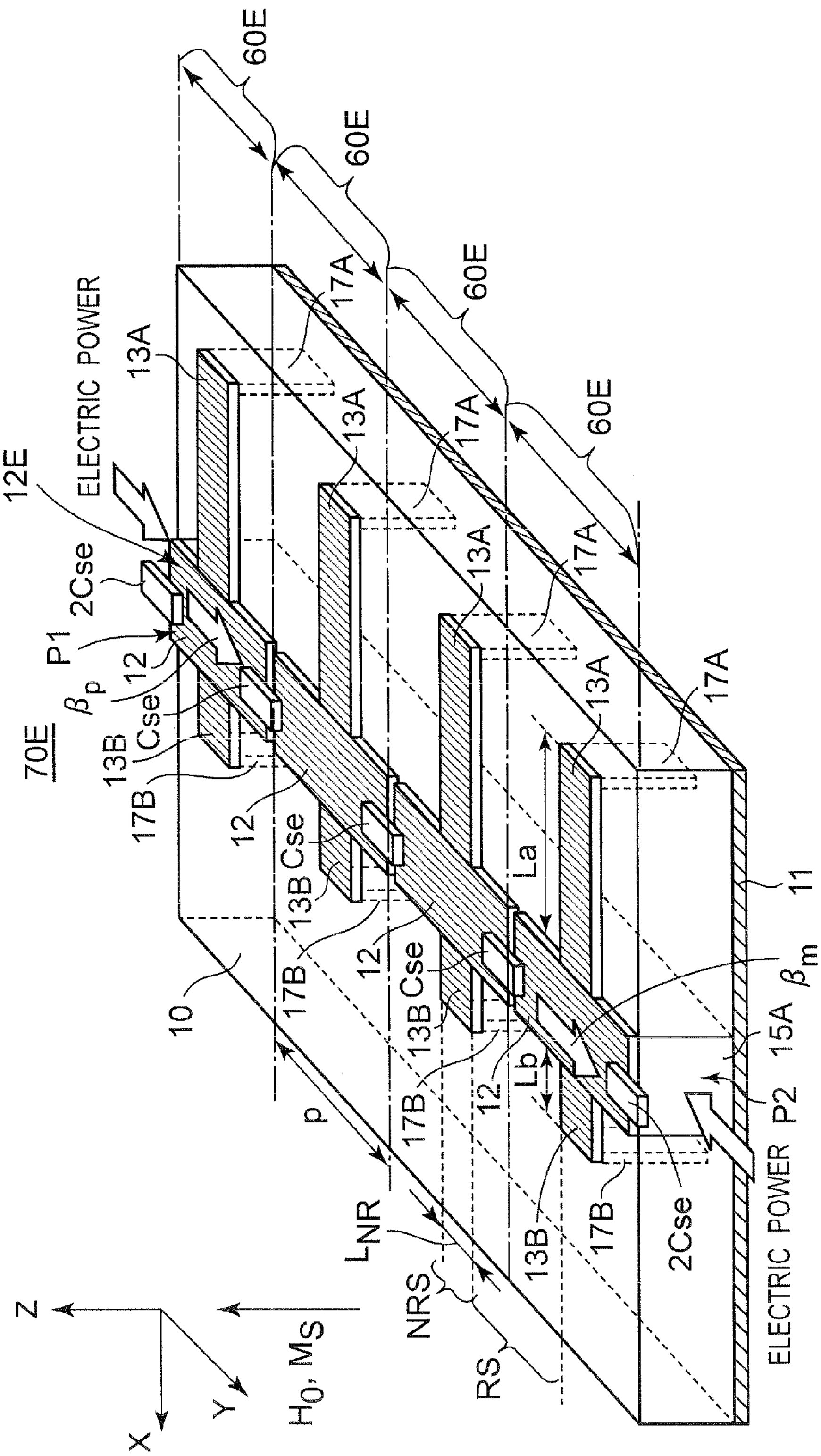


Fig.13A


70E
12E
ELECTRIC POWER
60E
60E
60E
60E
13A
13A
13A
13A
17A
17A
17A
17A
17A
2Cse
P1
12
β_p
Cse
13B
17B
12
Cse
13B
17B
12
Cse
13B
17B
12
La
Lb
11
β_m
15A
P2
2Cse
13B
17B
ELECTRIC POWER
10
p
L_{NR}
NRS
RS
Z
X
Y
H_0, M_S

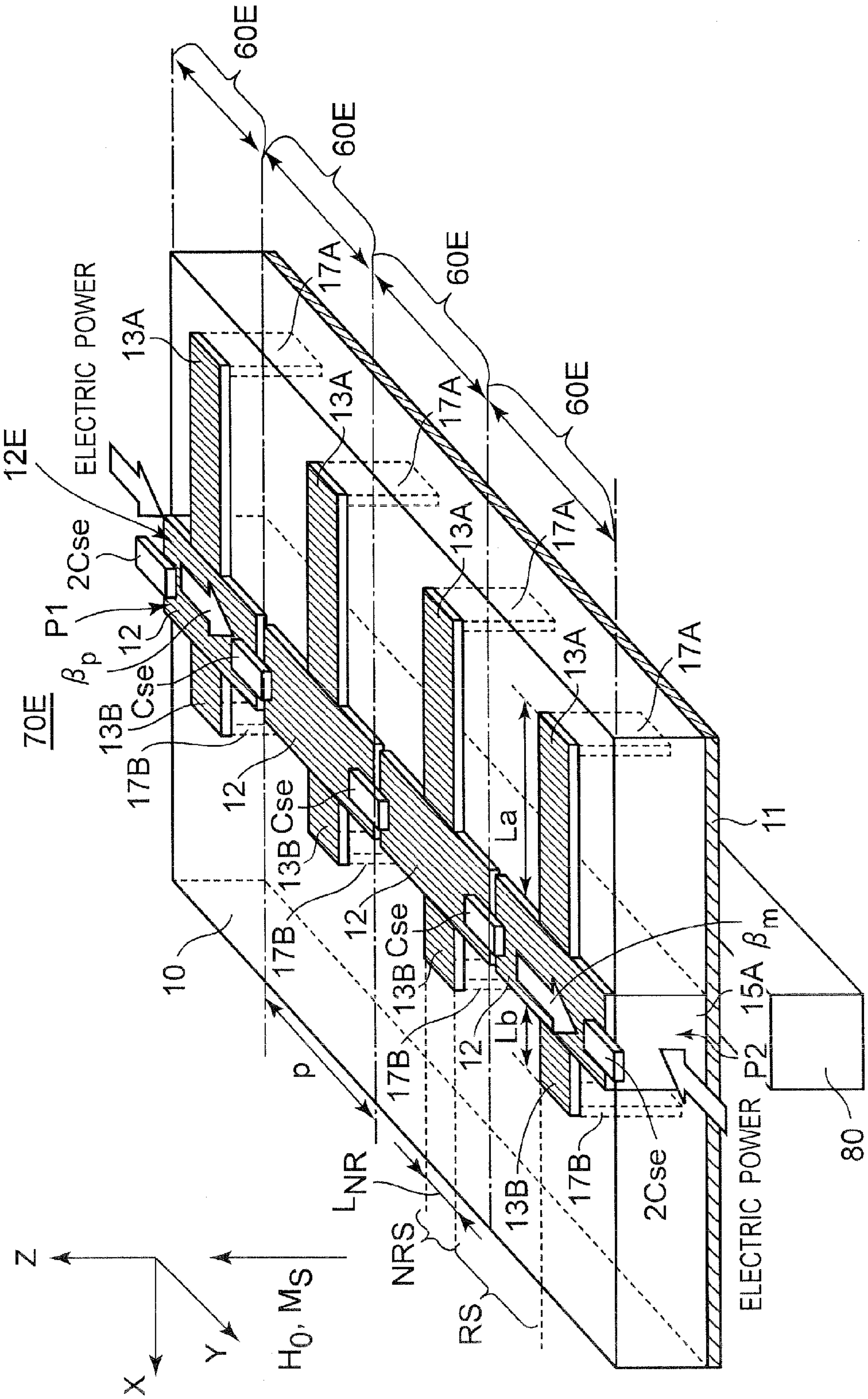

70E
60E
60E
60E
60E
17A
17A
17A
17A
13A
13A
13A
13A
ELECTRIC POWER
12E
2Cse
P1
12
βp
Cse
13B
17B
12
13B
Cse
17B
12
13B
Cse
17B
12
La
Lb
11
10
15A
βm
P2
80
13B
17B
2Cse
ELECTRIC POWER
p
LNR
NRS
RS
H0, MS
Z
Y
X

Fig. 13B

Fig.14

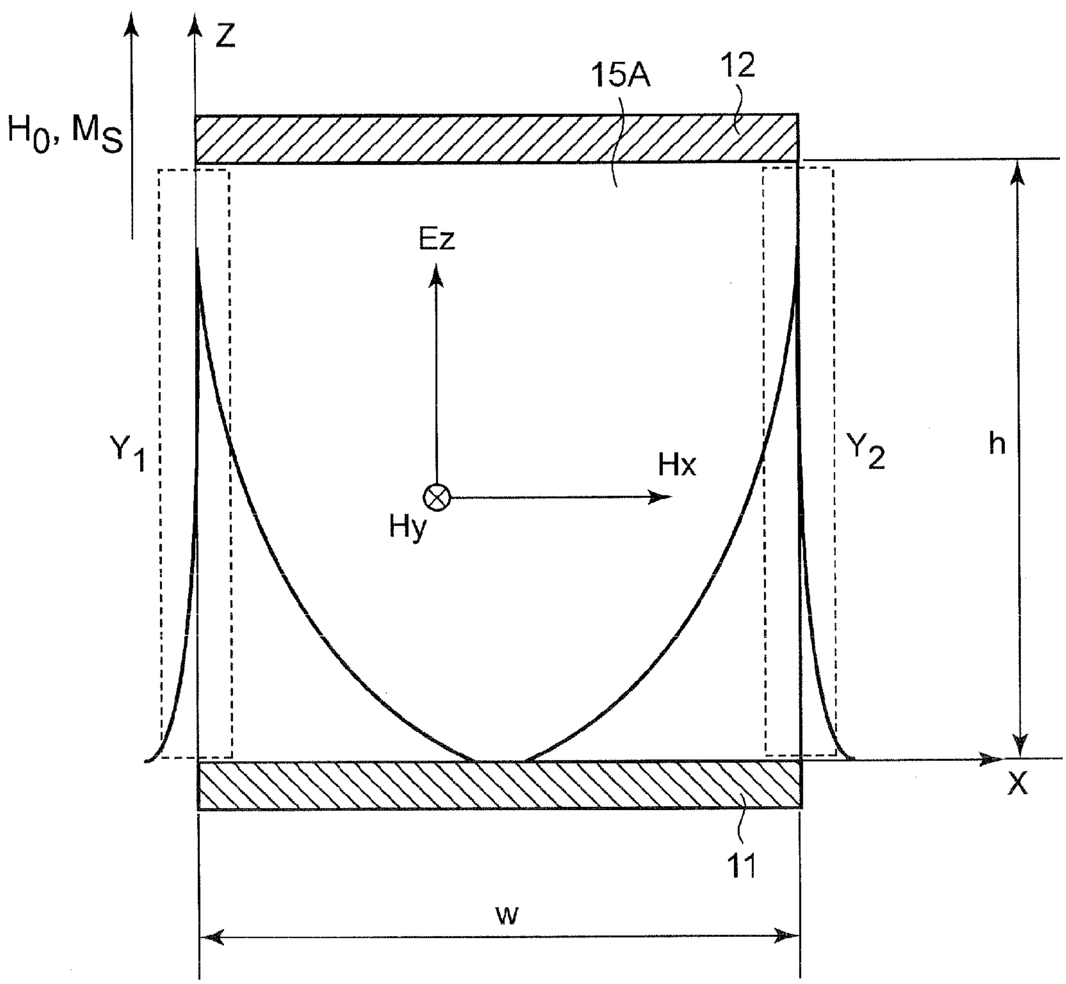


Fig.15

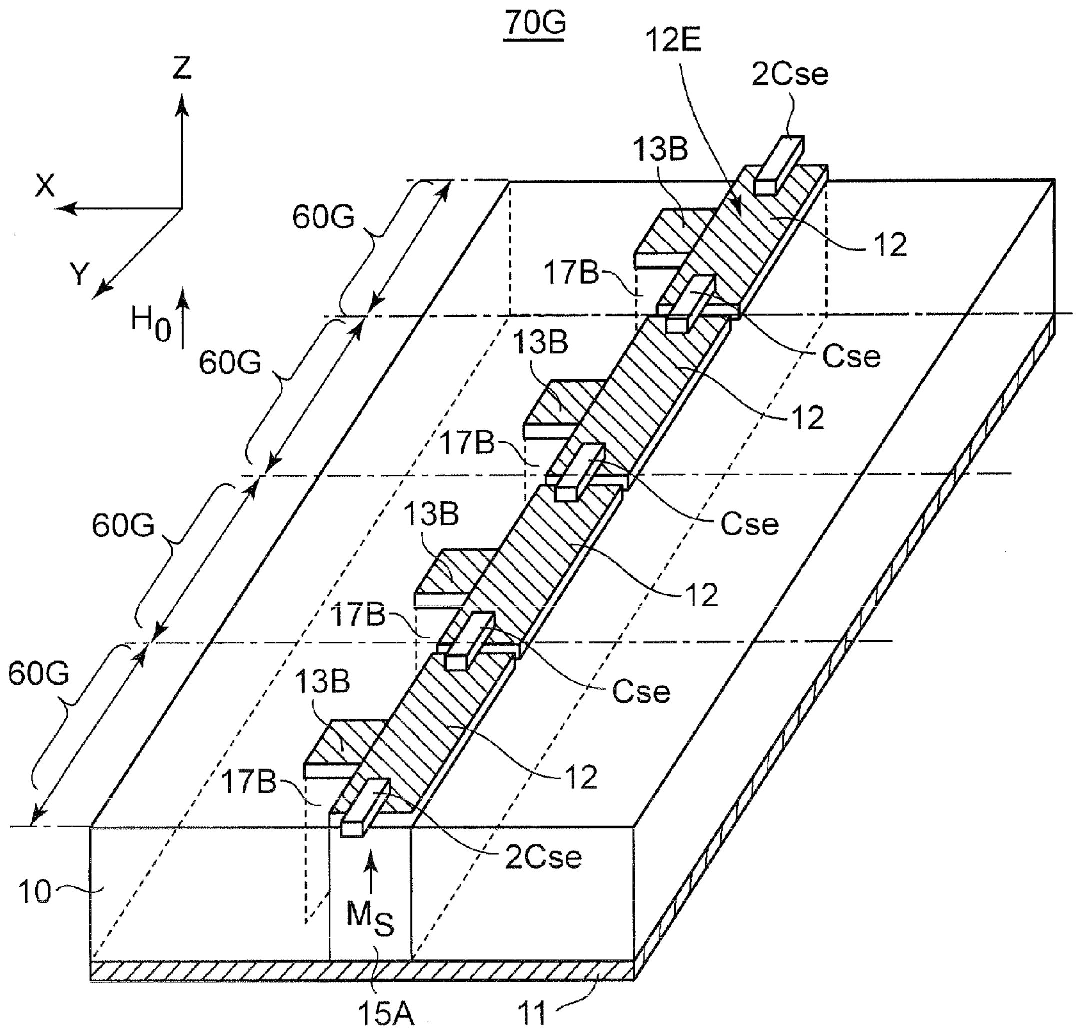
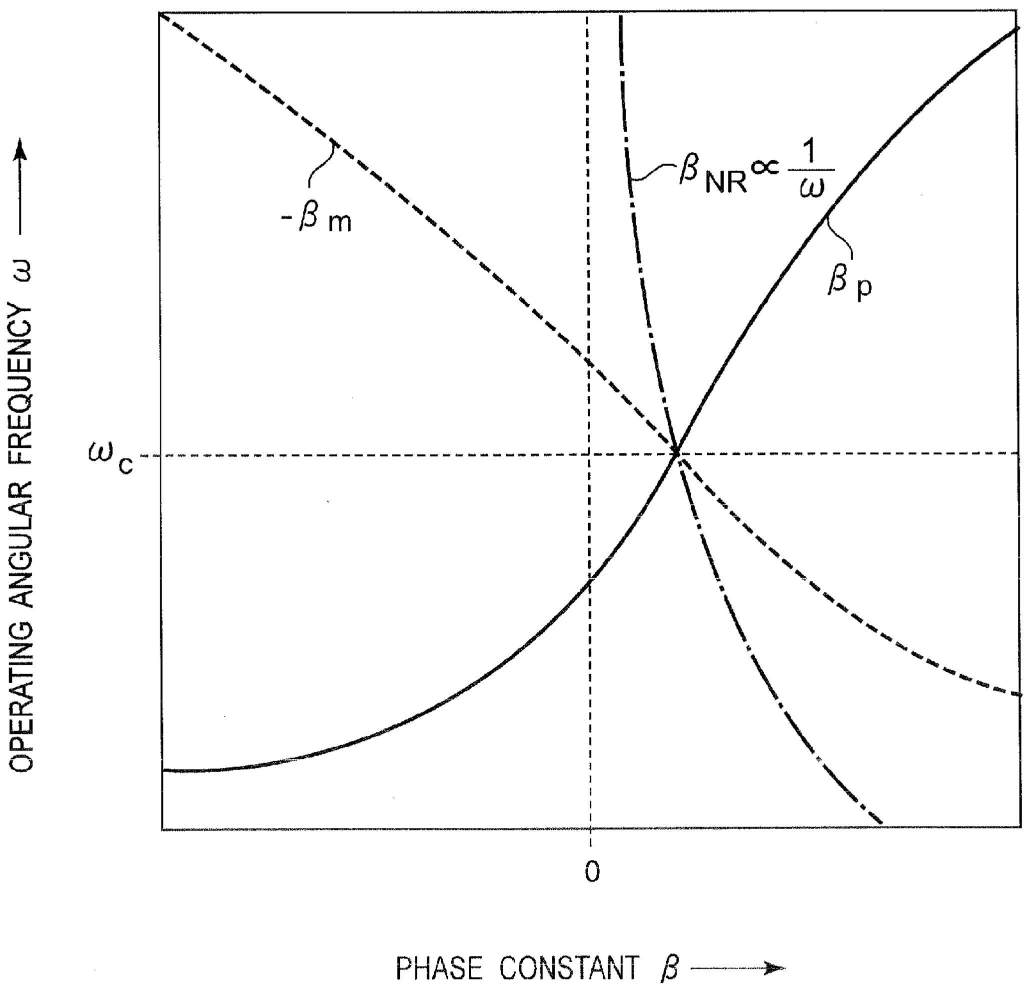


Fig. 16



-β m
β NR ∝ 1/ω
β p
ω c
0
OPERATING ANGULAR FREQUENCY ω
PHASE CONSTANT β

Fig.17

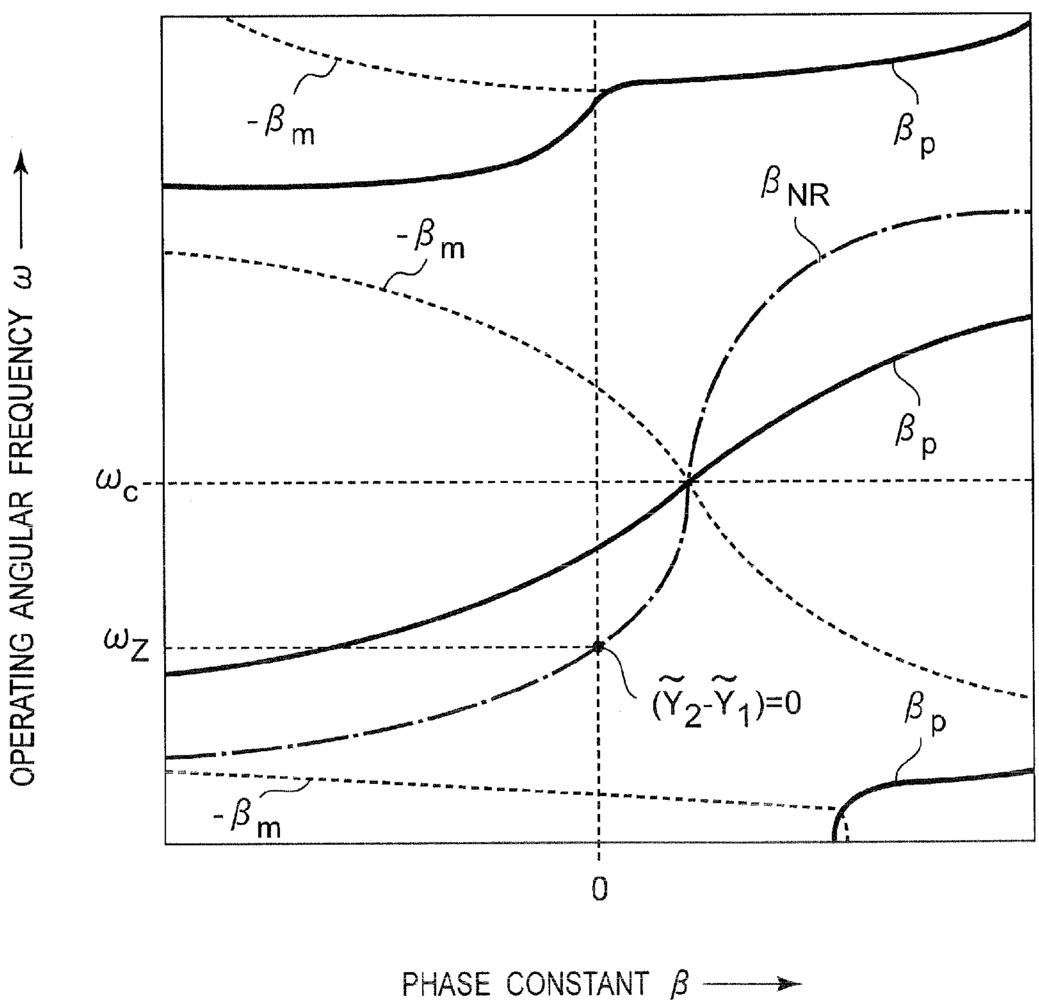
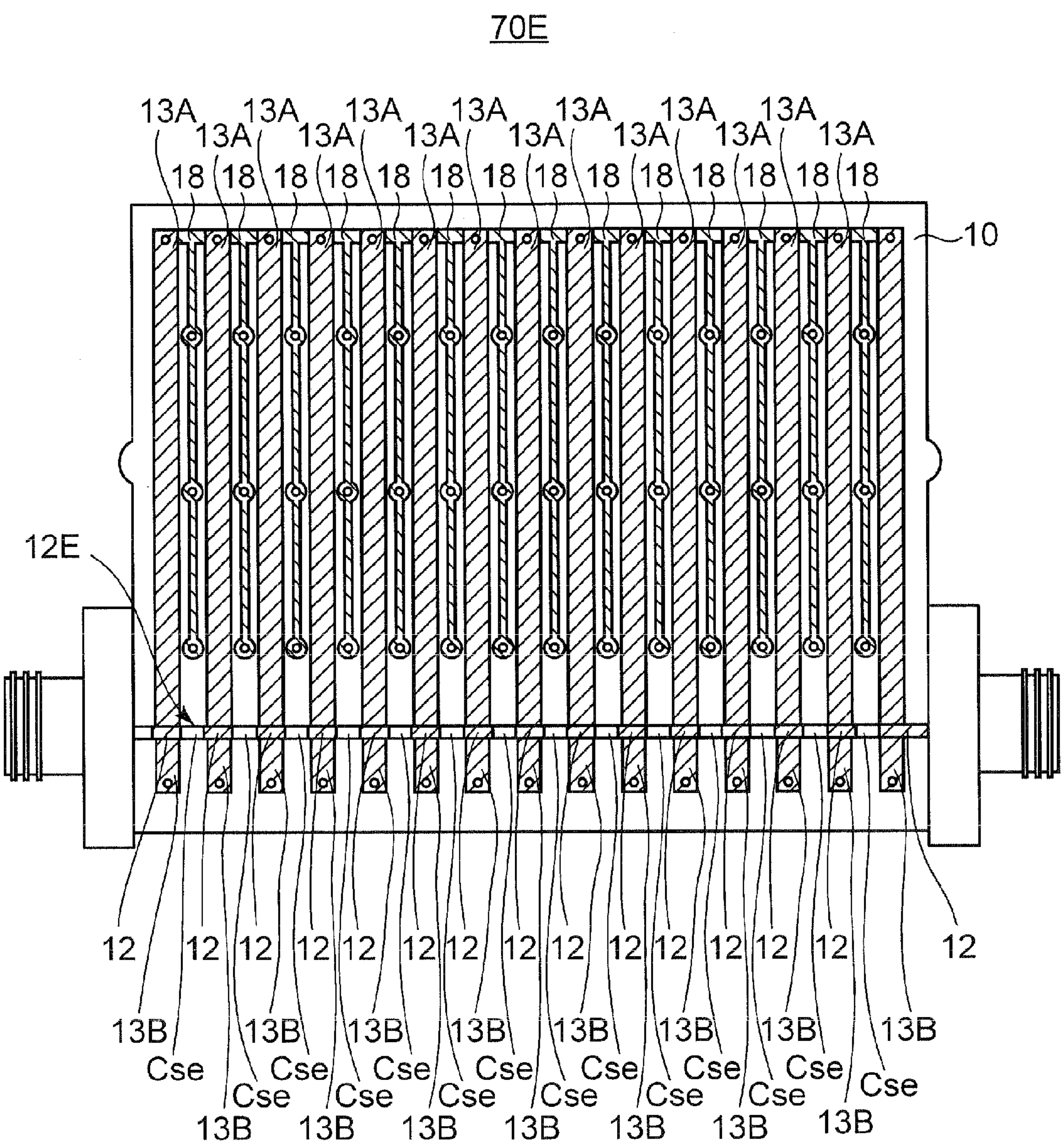
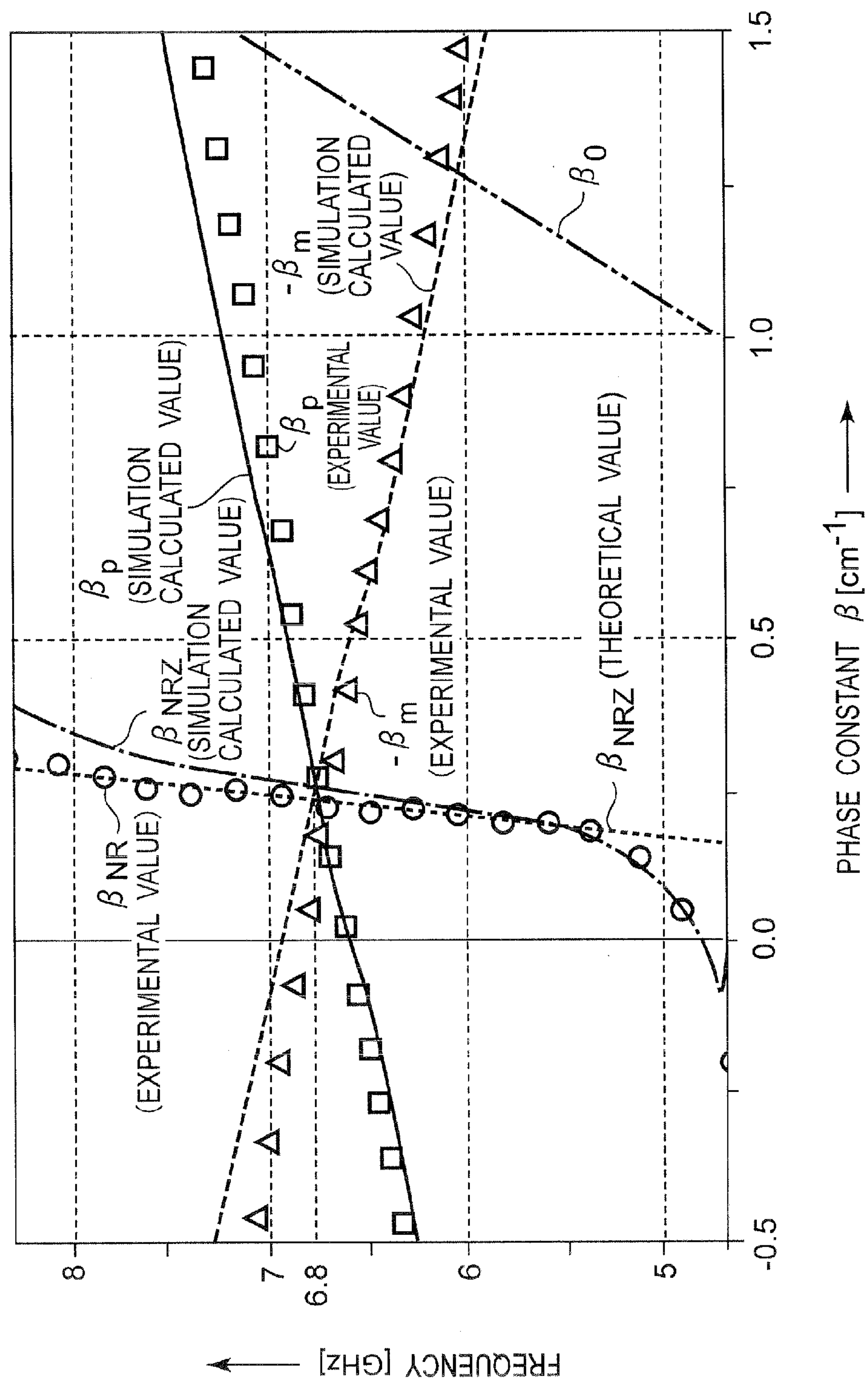

-β m
β p
β NR
-β m
β p
ω c
ω Z
(Ỹ2-Ỹ1)=0
β p
-β m
0
OPERATING ANGULAR FREQUENCY ω
PHASE CONSTANT β

Fig. 18





FREQUENCY [GHz]
8
7
6.8
6
5
PHASE CONSTANT β [cm-1]
-0.5
0.0
0.5
1.0
1.5
β0
-βm (SIMULATION CALCULATED VALUE)
βp (EXPERIMENTAL VALUE)
βp (SIMULATION CALCULATED VALUE)
βNRZ (SIMULATION CALCULATED VALUE)
-βm (EXPERIMENTAL VALUE)
βNRZ (THEORETICAL VALUE)
βNR (EXPERIMENTAL VALUE)

Fig.19

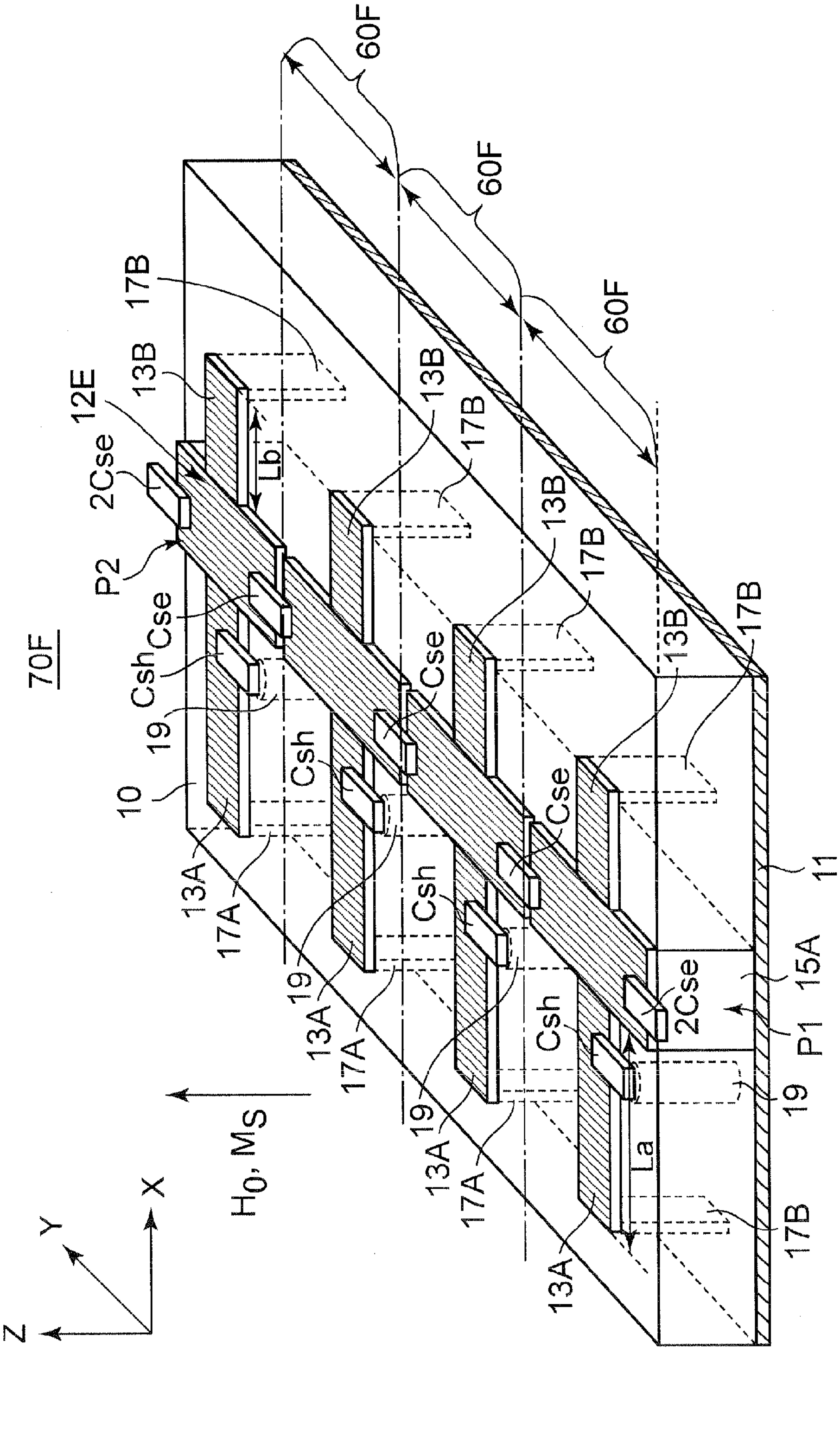

70F
60F
60F
60F
12E
2Cse
P2
Cse
Csh
Cse
Csh
Cse
Csh
Cse
Csh
2Cse
P1
13A
13B
17A
17B
19
10
11
15A
La
Lb
H_0, M_S
X
Y
Z

Fig.20A

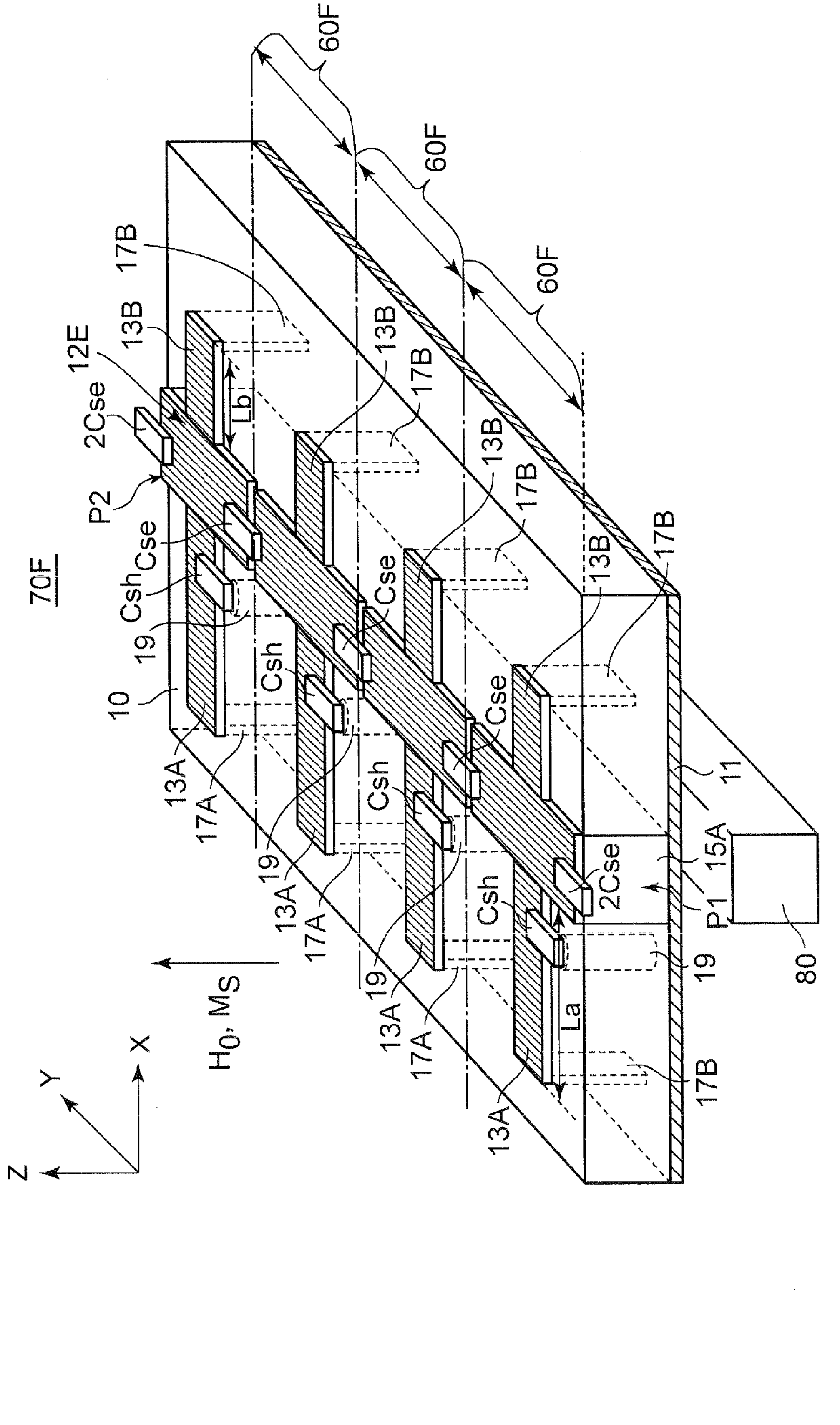
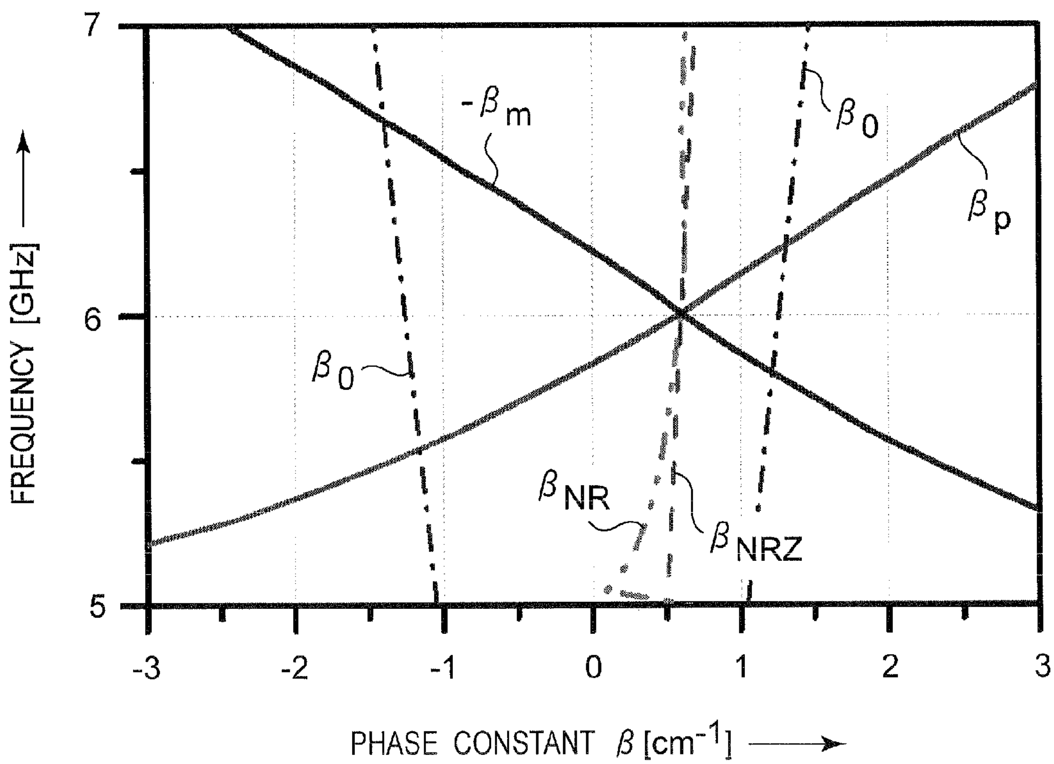

70F
60F
60F
60F
17B
13B
12E
2Cse
Lb
P2
Cse
Csh
19
10
13A
17A
Csh
Cse
13B
17B
Cse
Csh
19
13A
17A
Csh
Cse
13B
17B
13B
17B
13B
17B
19
13A
17A
Csh
La
13A
17B
2Cse
P1
15A
11
19
80
H_0, M_S
X
Y
Z

Fig.20B

Fig.21



7
6
5
-3
-2
-1
0
1
2
3
FREQUENCY [GHz]
PHASE CONSTANT β [cm-1]
-βm
β0
β0
βp
βNR
βNRZ

Fig.22

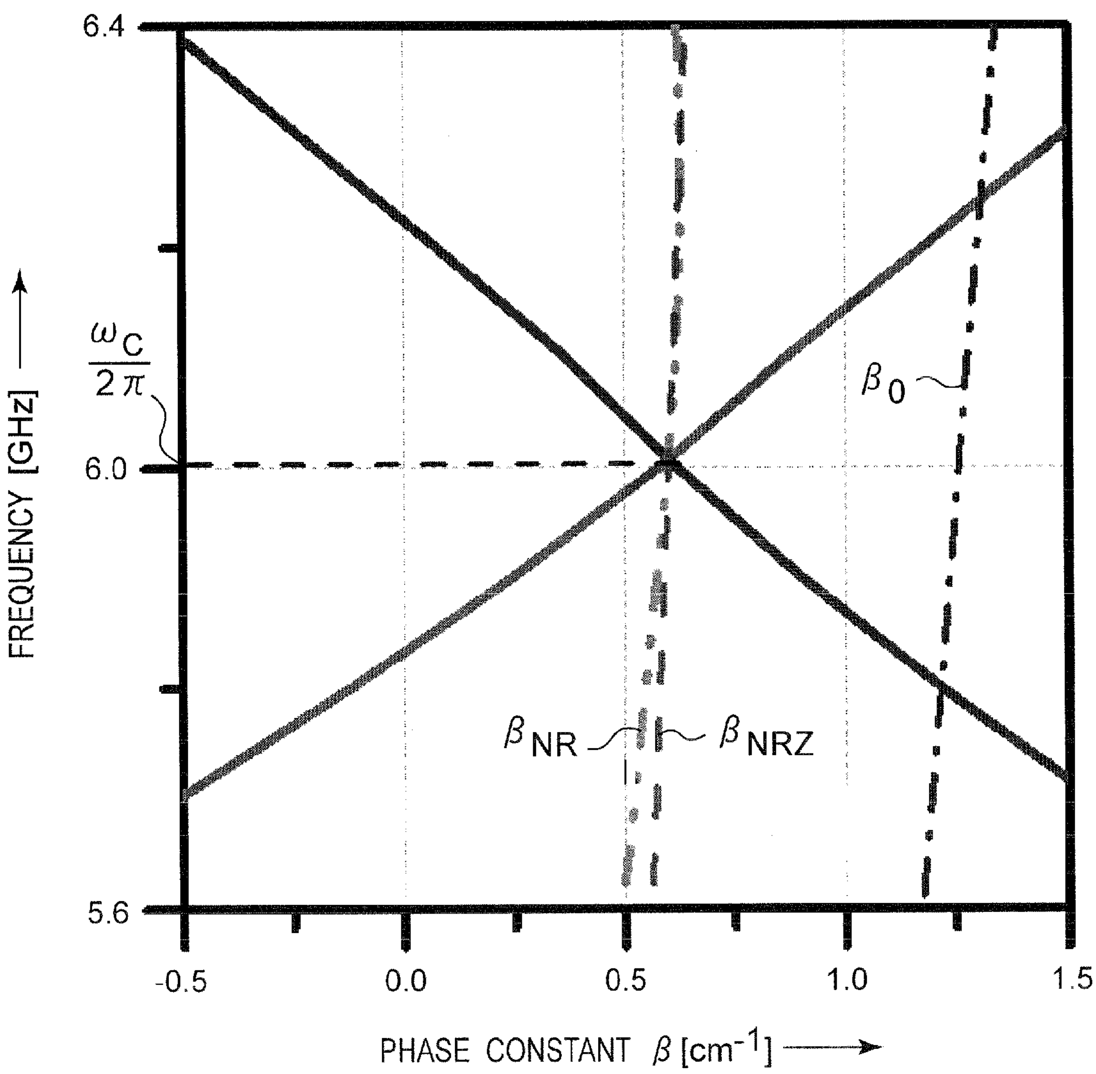

6.4
6.0
5.6
$\frac{\omega_C}{2\pi}$
FREQUENCY [GHz]
β_0
β_{NR}
β_{NRZ}
-0.5
0.0
0.5
1.0
1.5
PHASE CONSTANT β [cm^{-1}]

Fig.23

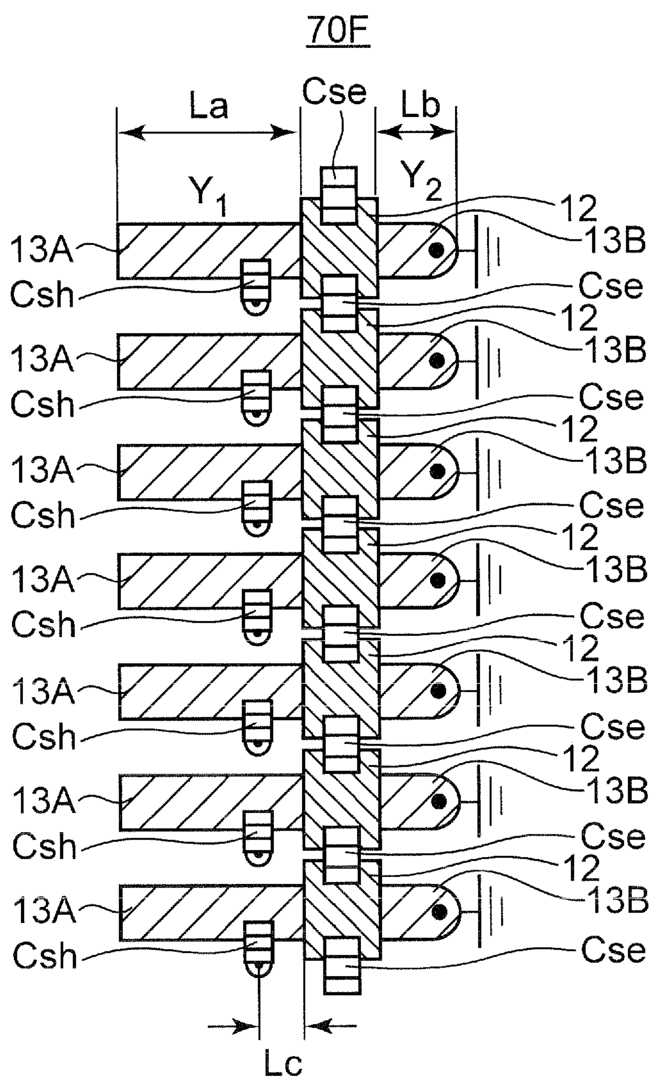


Fig.24

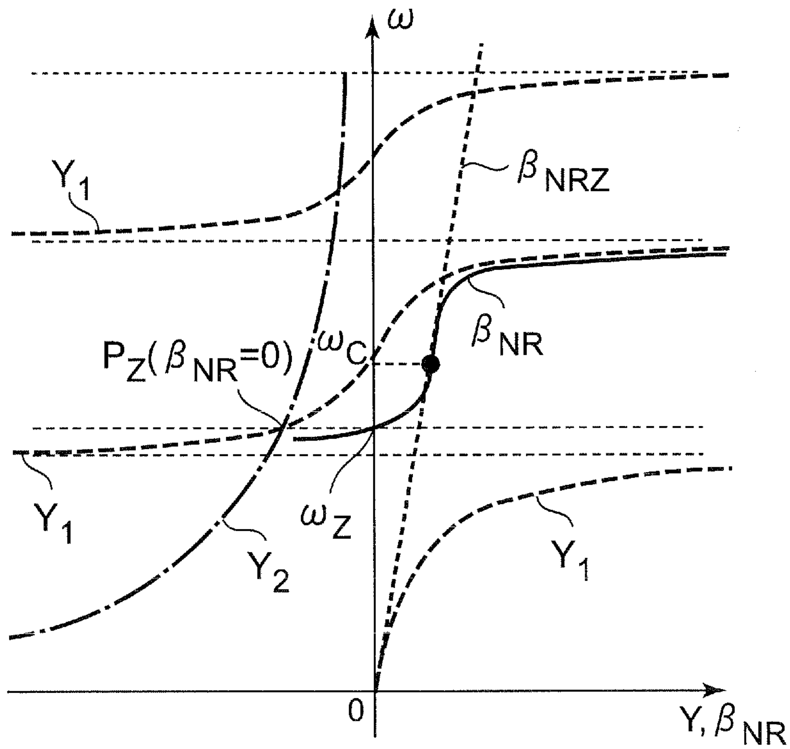
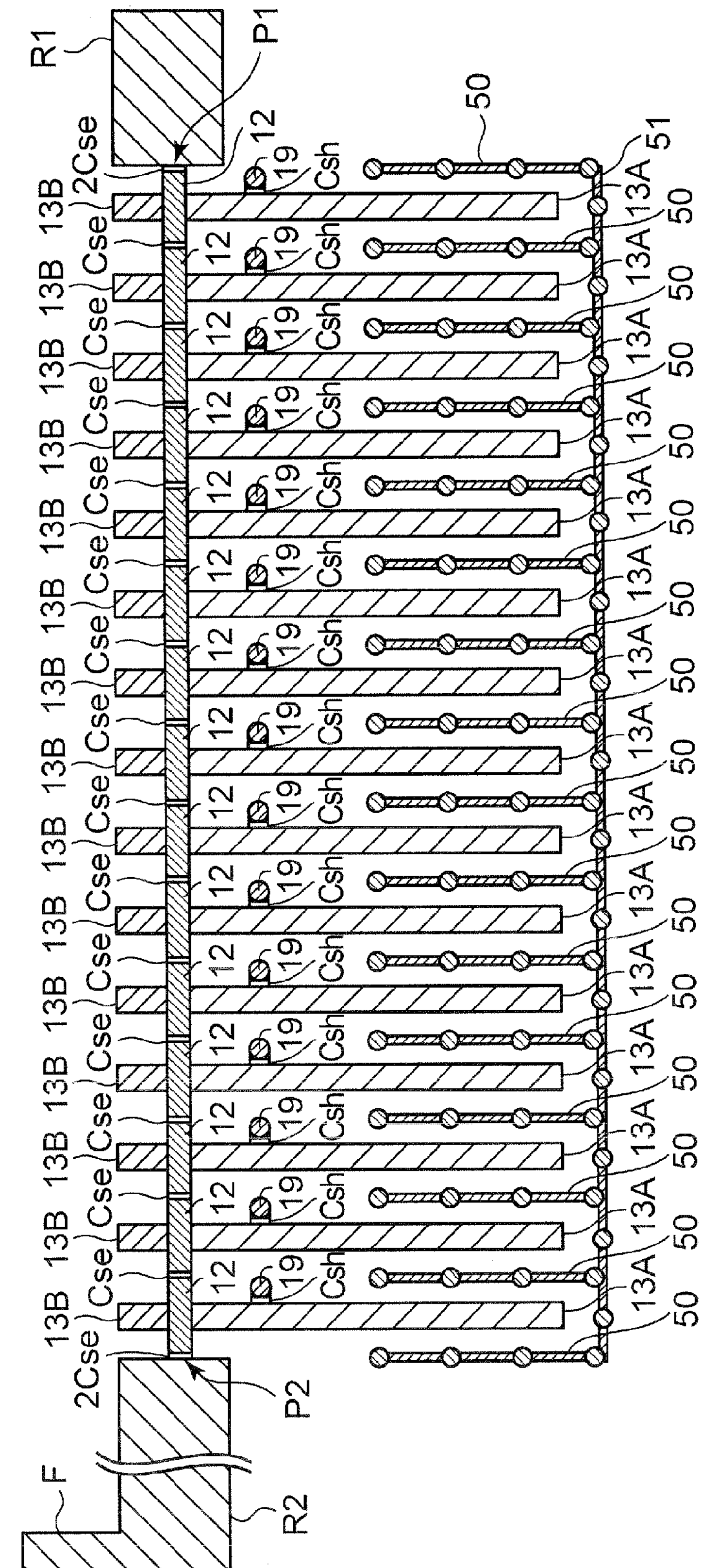


Fig.25

70F



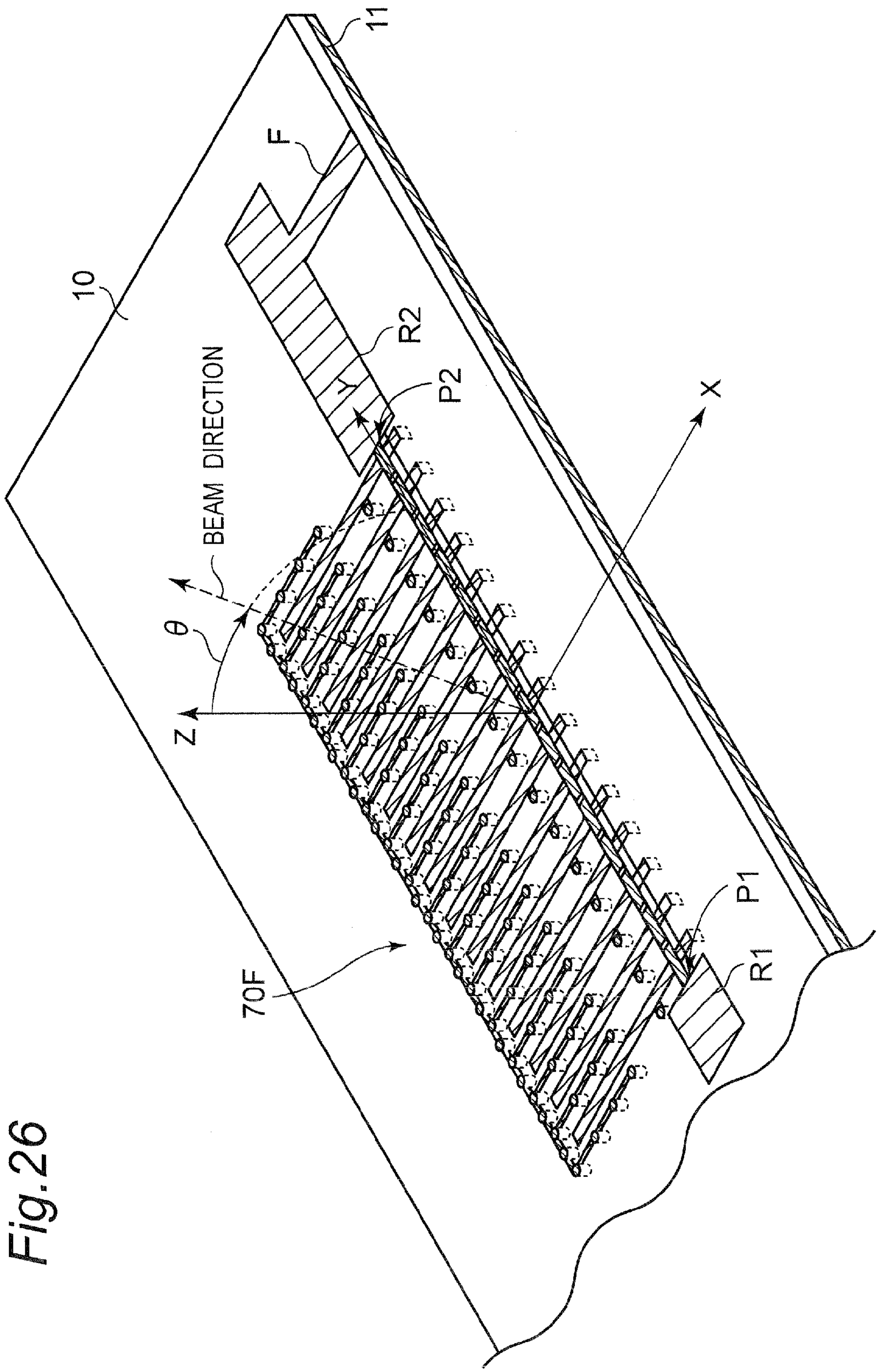


Fig.26

Fig.27

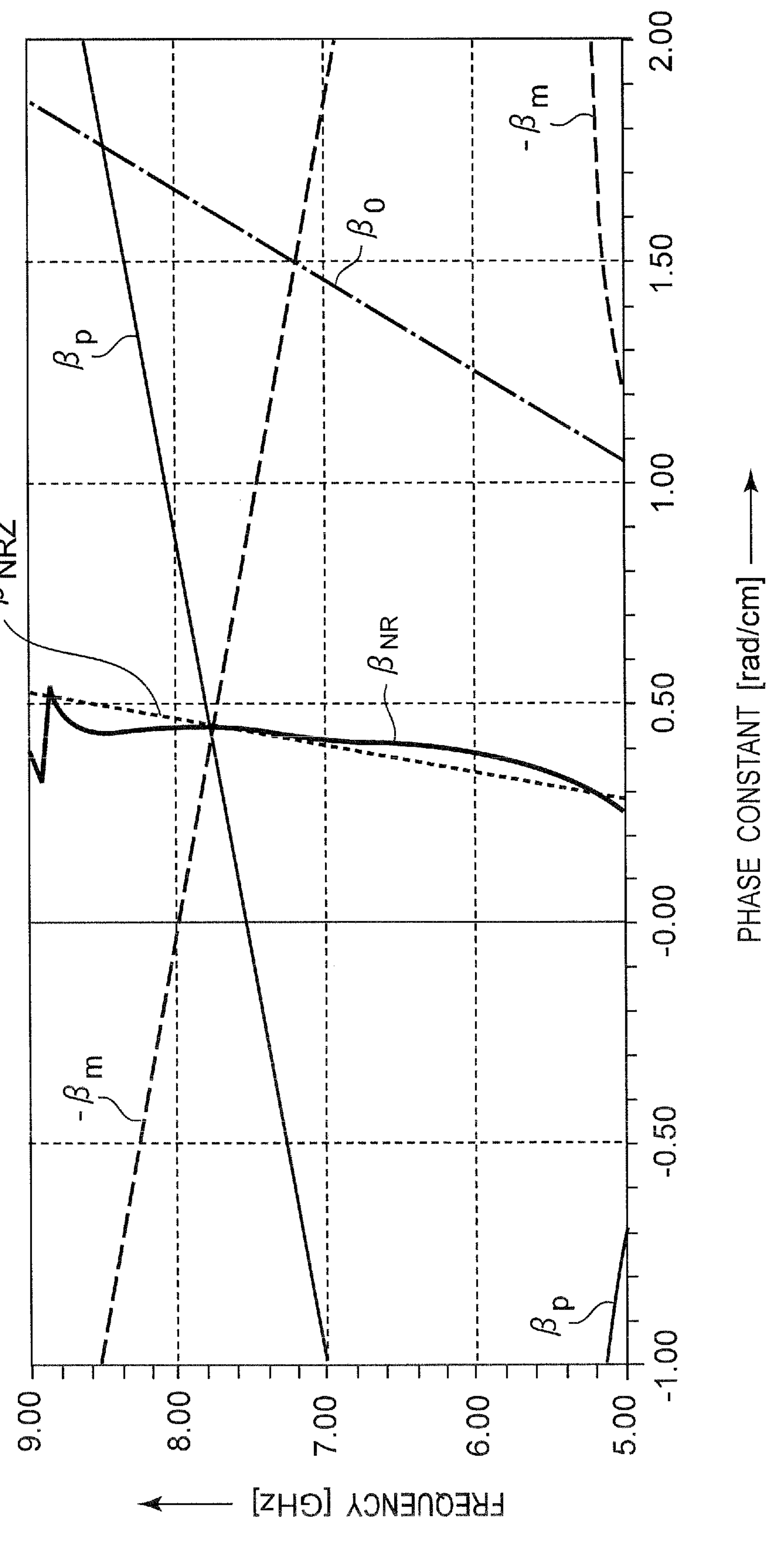

FREQUENCY [GHz]
PHASE CONSTANT [rad/cm]
9.00
8.00
7.00
6.00
5.00
-1.00
-0.50
-0.00
0.50
1.00
1.50
2.00
β_{NRZ}
β_{NR}
β_p
β_0
$-\beta_m$
$-\beta_m$
β_p

Fig.28

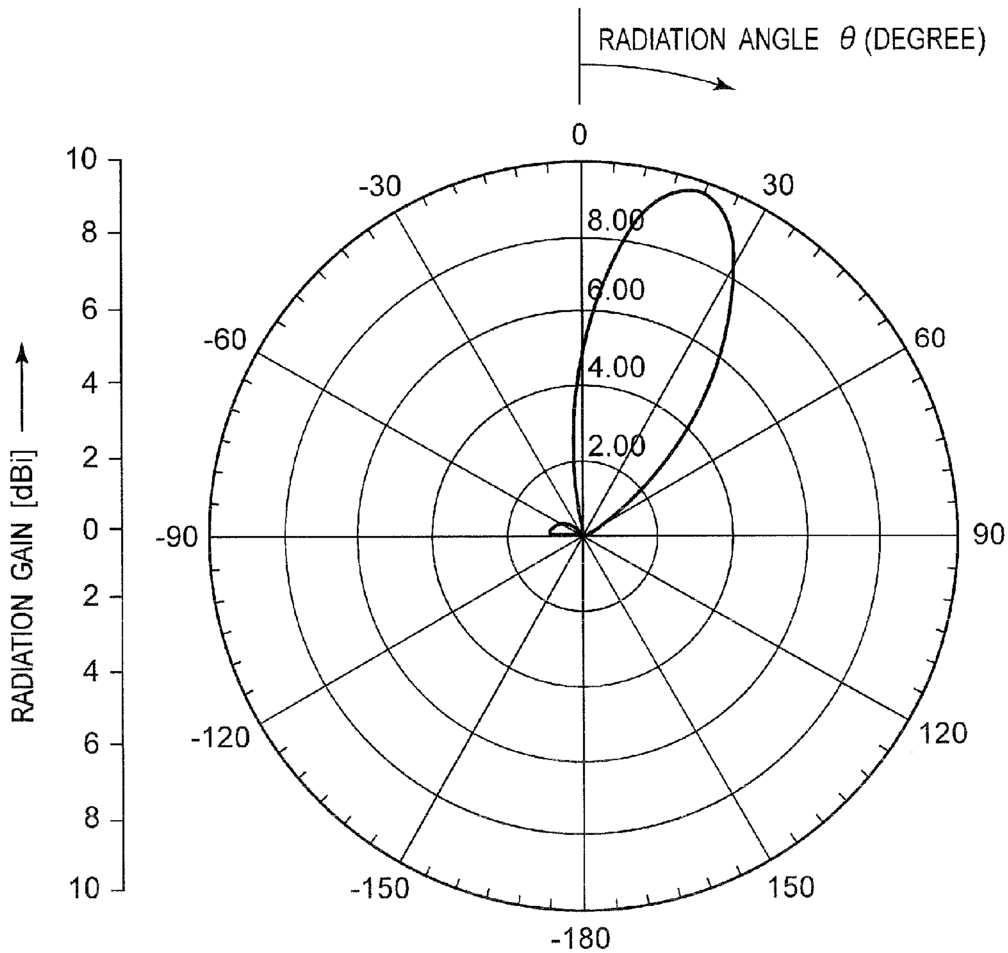

RADIATION ANGLE θ (DEGREE)
0
30
60
90
120
150
-180
-150
-120
-90
-60
-30
8.00
6.00
4.00
2.00
RADIATION GAIN [dBi]
10
8
6
4
2
0
2
4
6
8
10

Fig.29

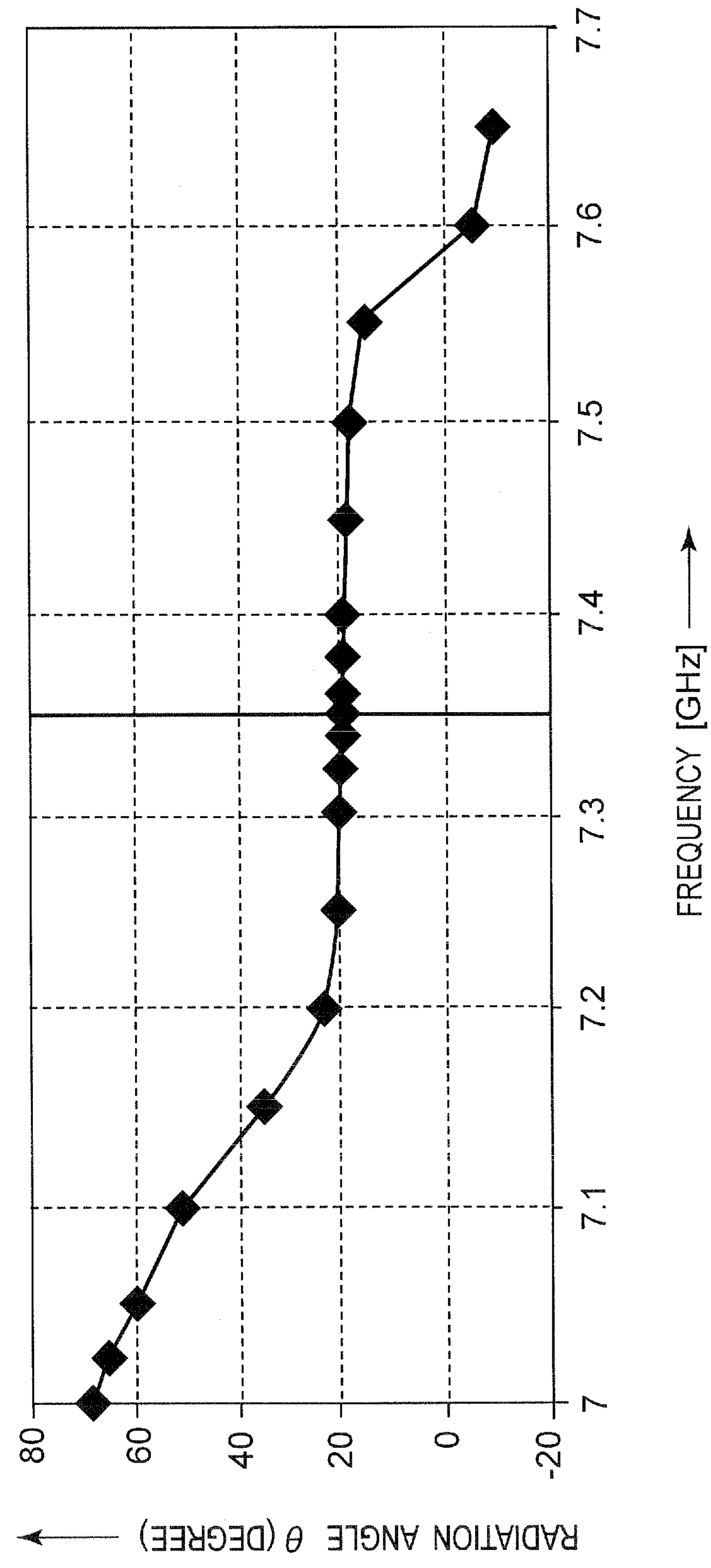

RADIATION ANGLE θ (DEGREE)
80
60
40
20
0
-20
7
7.1
7.2
7.3
7.4
7.5
7.6
7.7
FREQUENCY [GHz]

Fig.30

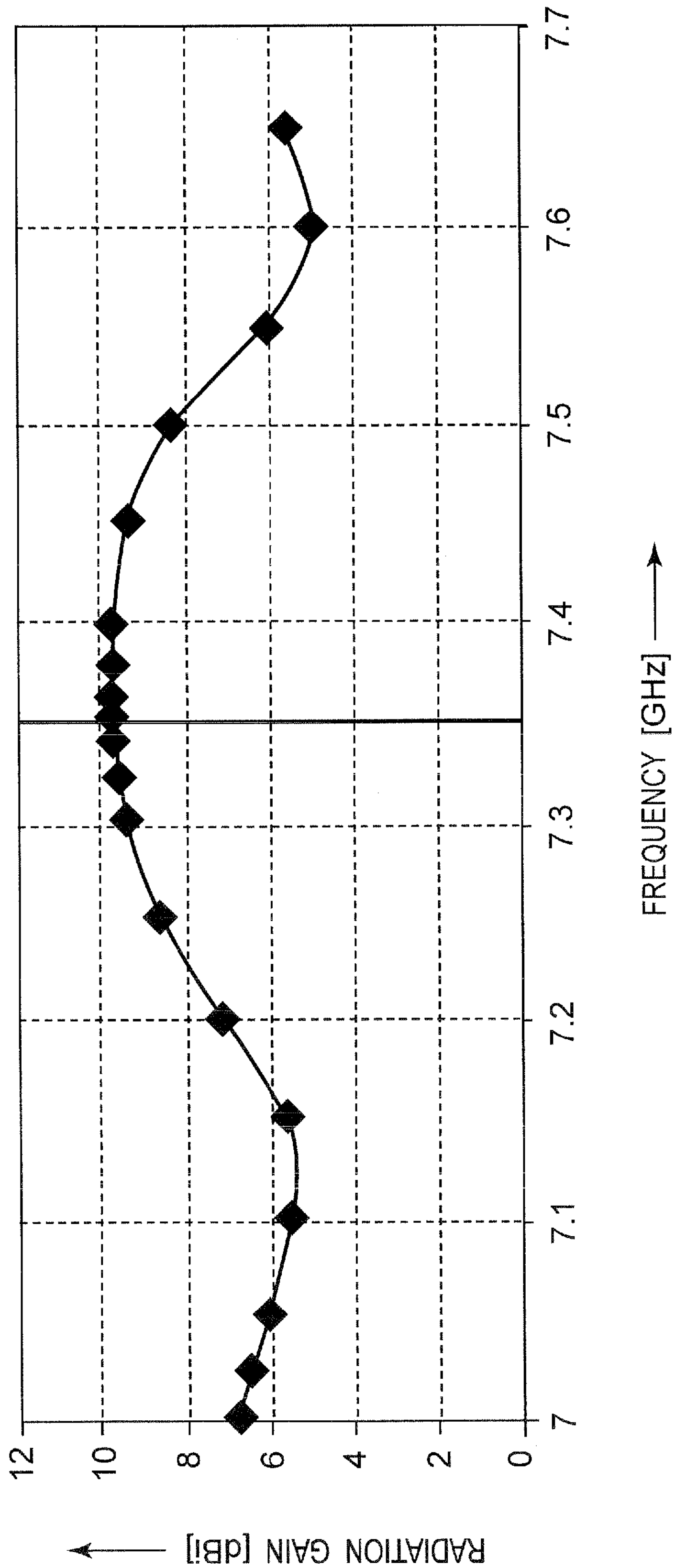

RADIATION GAIN [dBi]
FREQUENCY [GHz]
0
2
4
6
8
10
12
7
7.1
7.2
7.3
7.4
7.5
7.6
7.7

Fig.31A

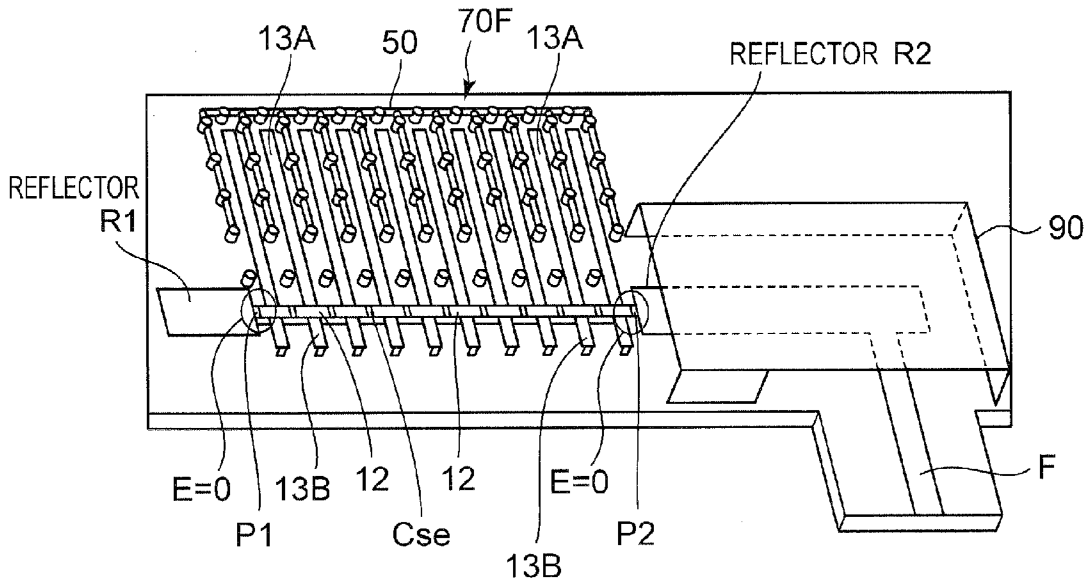


Fig.31B

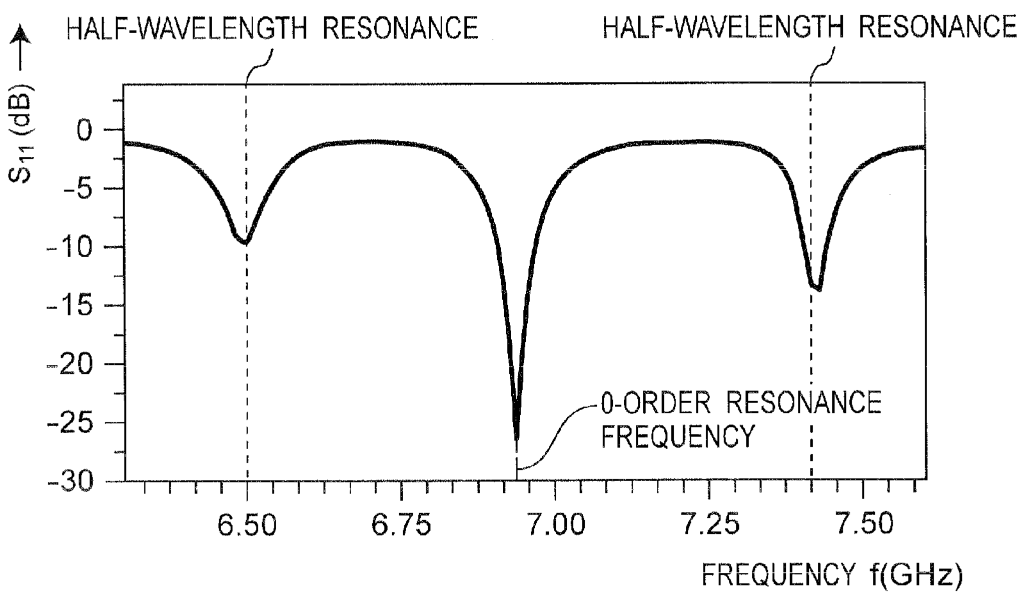


Fig.31C

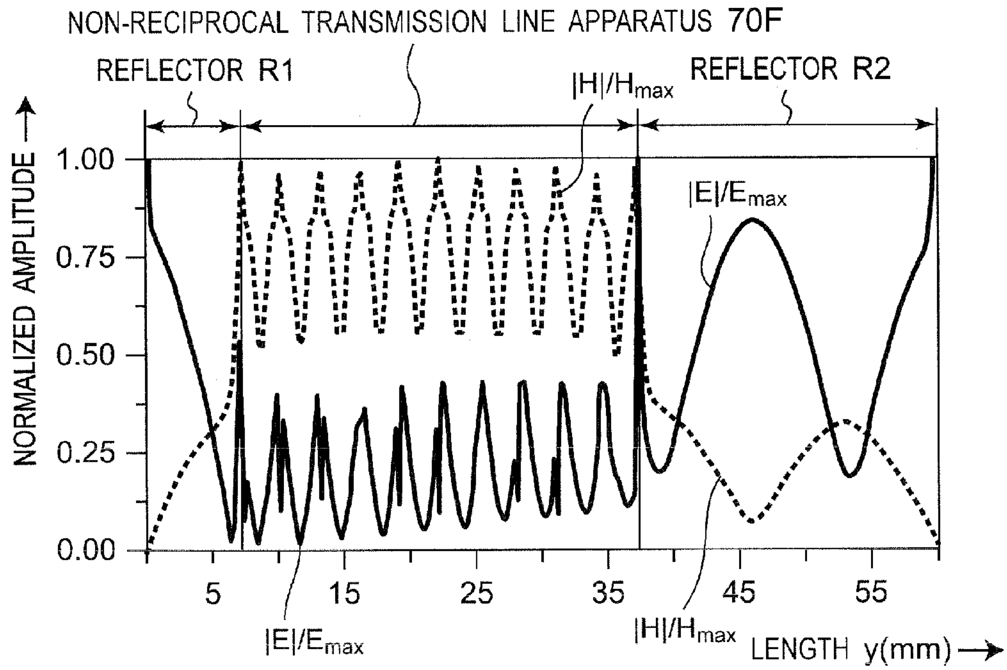


Fig.31D

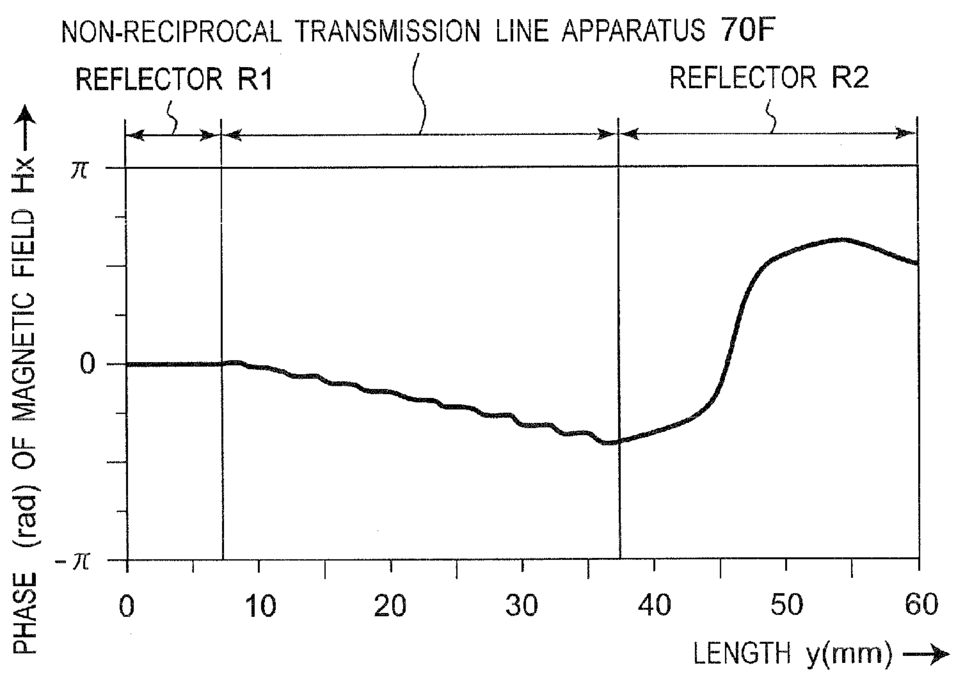


Fig.31E

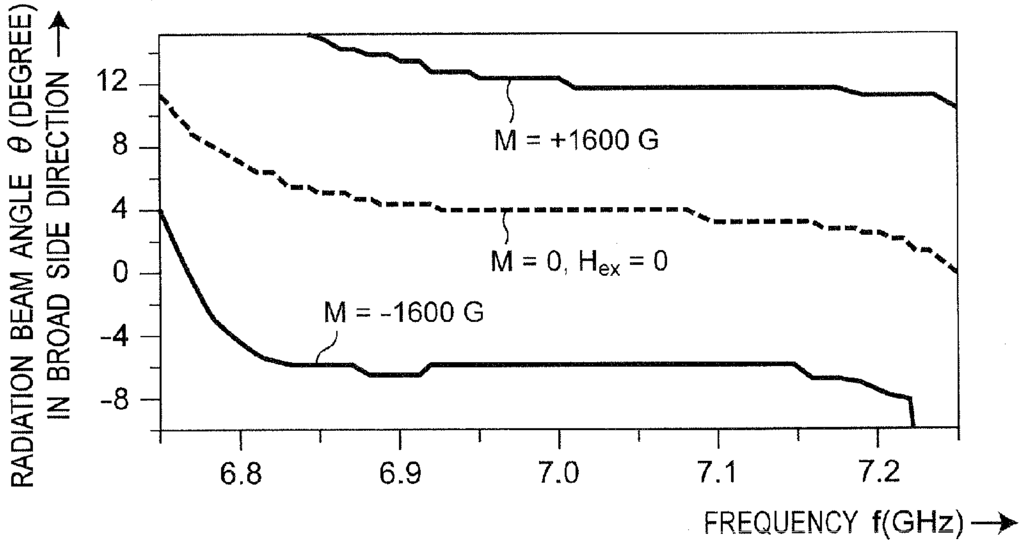


Fig.31F

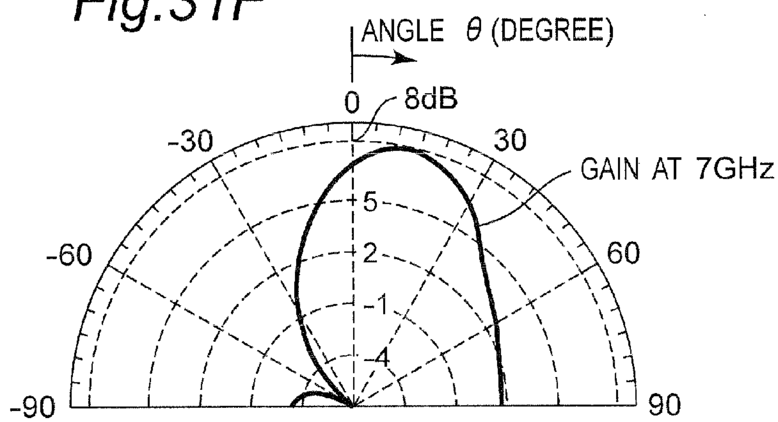


Fig.32A

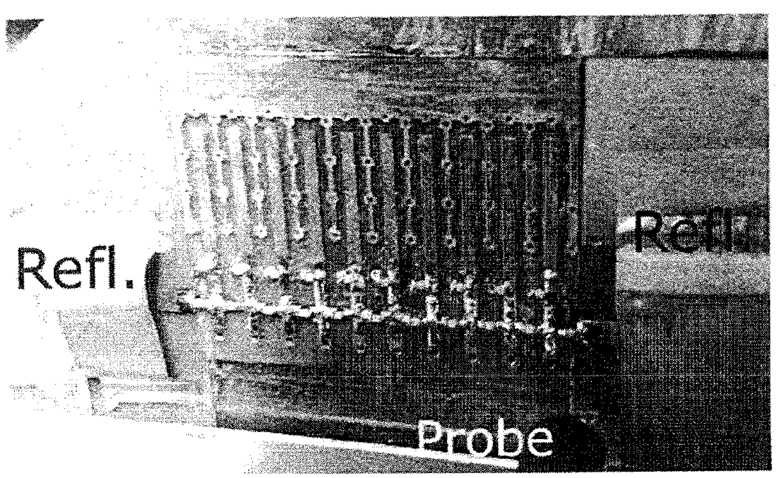


Fig.32B

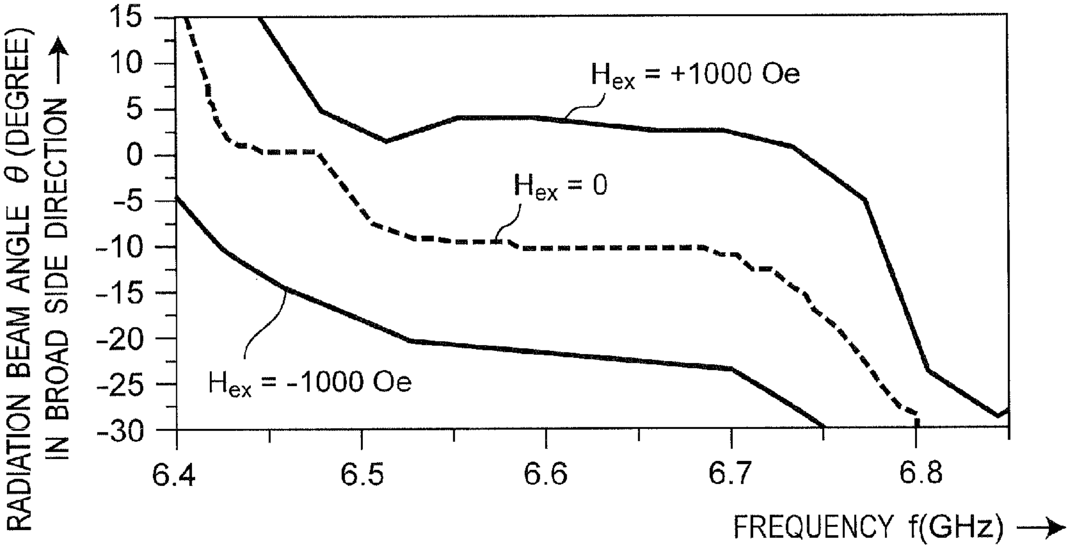
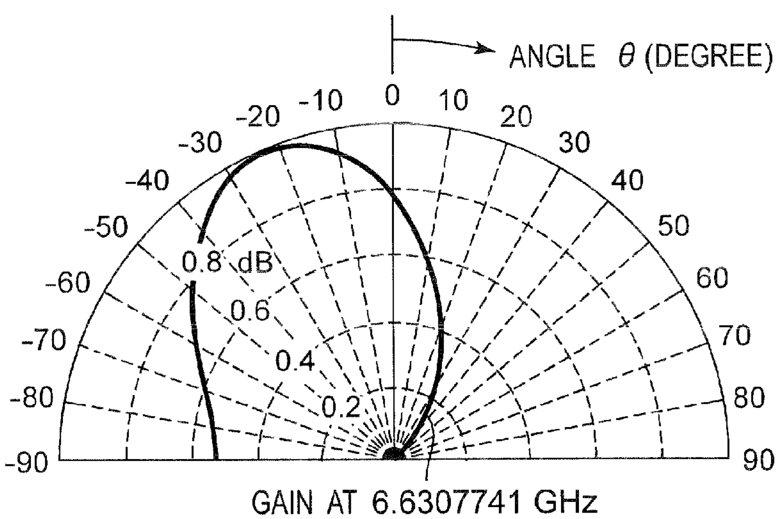


Fig.32C



NONRECIPROCAL TRANSMISSION LINE APPARATUS WHOSE PROPAGATION CONSTANTS IN FORWARD AND BACKWARD DIRECTIONS ARE DIFFERENT FROM EACH OTHER

TECHNICAL FIELD

The present invention relates to a nonreciprocal transmission line apparatus whose propagation constant in a forward direction and propagation constant in a backward direction are different from each other, and further relates to an antenna apparatus including the same nonreciprocal transmission line apparatus.

BACKGROUND ART

A composite right/left-handed transmission line (hereinafter, referred to as a CRLH (Composite Right/left-Handed) transmission line) has been known as one of metamaterials. The CRLH transmission line is configured by substantially periodically inserting capacitive elements in series branch of the transmission line and substantially periodically inserting inductive elements in shunt branch, at intervals sufficiently smaller than the wavelength so as to have a negative effective permeability and a negative effective dielectric constant in a predetermined frequency band. In recent years, a nonreciprocal phase shift CRLH transmission line obtained by adding a nonreciprocal transmission function to the CRLH transmission line has been proposed (See, for example, Patent Documents 1 to 3). The nonreciprocal phase shift CRLH transmission line is able to exhibit a positive refractive index when electromagnetic waves having an identical frequency propagate in the forward direction and to exhibit a negative refractive index when the electromagnetic waves propagate in the backward direction.

When the transmission line resonator is configured by using the nonreciprocal phase shift CRLH transmission line, the resonator size can be freely changed without changing the resonance frequency. Further, the electromagnetic field distribution on the resonator is similar to the electromagnetic field distribution of a traveling wave resonator. Therefore, by using a transmission line resonator having the nonreciprocal phase shift CRLH transmission line, a pseudo traveling wave resonator can be configured such that an amplitude of the electromagnetic field of the pseudo traveling wave resonator is uniform and a phase of the electromagnetic field of the pseudo traveling wave resonator linearly changes with a constant gradient along the transmission line. In this case, the phase gradient of the electromagnetic field distribution on the resonator is determined by the nonreciprocal phase shift characteristic of the transmission line configuring the resonator. Hereinafter, the transmission line apparatus using the nonreciprocal phase shift CRLH transmission line is referred to as a nonreciprocal transmission line apparatus.

The metamaterials have been a very interesting important theme in the field of applications to antennas for more than a decade. The nonreciprocal CRLH metamaterial has been proposed for the purpose of applications to directional leaky wave antenna using the CRLH transmission line until now. Moreover, recently, an antenna based on the pseudo traveling wave resonator highly developed from the zeroth-order resonator (See, for example, Non-Patent Document 1) has been proposed, so that the gain and the directivity are increased in spite of compactness as compared with the conventional leaky wave antenna.

Many ones of the nonreciprocal transmission line apparatuses that have been proposed until now adopt such a structure that a ferrite rod perpendicularly magnetized is embedded under the strip line at the center of the composite right/left-handed transmission line apparatus configured of the conventional microstrip line. In this case, the direction of the radiation beam from the antenna apparatus having the pseudo traveling wave resonator configured of the nonreciprocal transmission line apparatus is determined by the phase gradient of the electromagnetic field distribution on the resonator. Moreover, if the ferrite is a soft magnetic material, the nonreciprocal phase shift characteristic of the transmission line is changed by changing the magnitude or the direction of an externally applied magnetic field, and beam scanning can consequently be performed.

For example, Non-Patent Document 1 proposes application of the pseudo traveling wave resonator having the nonreciprocal transmission line apparatus to a beam-scanning antenna. The beam scanning antenna having the pseudo traveling wave resonator has such a drawback that the operation band is narrow, however, the beam scanning antenna has higher radiation efficiency than that of the conventional leaky wave antenna. Further, the problem of the occurrence of beam squint, which is such a phenomenon that the radiation beam direction changes in accordance with the frequency change of the propagation signal, is largely reduced.

The beam squint is a phenomenon well known in the conventional phased array antenna, or such a phenomenon that the beam radiation angle fluctuates depending on the frequency. The operation bandwidth is disadvantageously suppressed by this (See, for example, Non-Patent Document 6). In the ordinary array antenna, the main cause of the beam squint is in the dispersibility of the delay element. As one method for solving this, there can be enumerated a tunable time delay element used as an active CRLH delay element disclosed in Non-Patent Document 8. In the case of the CRLH metamaterial, this kind of compensation circuit is meaningless, and it has been possible to reduce the beam squint only in the upper bands of the series resonance frequency of the series branch and the parallel resonance frequency of the shunt branch (See, for example, Non-Patent Document 7).

PRIOR ART DOCUMENTS

Patent Documents

Patent Document 1: International Application Publication No. WO2008/111460A;

Patent Document 2: International Application Publication No. WO2011/024575A; and

Patent Document 3: International Application Publication No. WO2012/115245A.

Non-Patent Document 1: T. Ueda et al., "Pseudo traveling-wave resonator with magnetically tunable phase gradient of fields and its applications to beam steering antennas", IEEE Transactions on Microwave Theory and Techniques, vol. 60, no. 10, pp. 3043-3054, October 2012;

Non-Patent Document 2: M. E. Hines, "Reciprocal and nonreciprocal modes of propagation in ferrite stripline and microstrip devices", IEEE Transactions on Microwave Theory and Techniques, vol. MTT-19, no. 5, pp. 442-451, May 1971;

Non-Patent Document 3: A. Porokhnyuk et al., "Mode analysis of nonreciprocal metamaterials using a combination of field theory and transmission line model", 2012

IEEE MTT-S International Microwave Symposium Digest, WE4J-5, pp. 1-3, June 2012;

Non-Patent Document 4: T. Ueda et al., "Nonreciprocal phase-shift CRLH transmission lines using geometrical asymmetry with periodically inserted double shunt stubs", Proceedings of the 42nd European Microwave Conference, pp. 570-573, October 2012;

Non-Patent Document 5: A. Mahmoud et al., "Design and analysis of tunable left handed zeroth-order resonator on ferrite substrate", IEEE Transactions on magnetics, vol. 44, no. 11, pp. 3095-3098, November 2008;

Non-Patent Document 6: S. K. Garakoui et al., "Phased-array antenna beam squinting related to frequency dependency of delay circuits", Proceedings of the 41st European Microwave Conference, pp. 1304-1307, October 2011;

Non-Patent Document 7: M. A. Antoniades et al., "A CPS leaky-wave antenna with reduced beam squinting using NRI-TL metamaterials", IEEE Transactions on antennas and propagation, vol. 56, no. 3, March 2008; and

Non-Patent Document 8: H. V. Nguyen et al., "Analog dispersive time delayer for beam-scanning phased-array without beam-squinting", 2008 IEEE AP-S International Symposium, Digital Object Identifier: 10.1109/APS.2008.4619097, 2008.

DISCLOSURE OF INVENTION

Problems to be Dissolved by the Invention

In a reciprocal zeroth-order resonant leaky wave antenna, any problem of the beam squint does not occur. Because the dispersion characteristic of the traveling wave propagating in one direction is completely cancelled by the dispersion characteristic of the reflected wave propagating in the opposite direction. However, the resonance type leaky wave antenna consisting of the nonreciprocal CRLH transmission line has become able to control the radiation angle, and this leads to that the phase constant differs between the traveling wave and the reflected wave propagating in the resonator. Consequently, the frequency dispersion characteristic of the nonreciprocal phase shift amount obtained from the average value of the phase constant in the case of forward travel and the phase constant in the case of backward travel causes beam squint. There has been proposed no method for substantially preventing the occurrence of the beam squint until now, and no effective means is found.

An object of the present invention is to solve the aforementioned problems, and provide a nonreciprocal transmission line apparatus that substantially prevents the beam squint from occurring in the vicinity of the center frequency of the operation band and an antenna apparatus having the nonreciprocal transmission line apparatus.

Means for Dissolving the Problems

According to the first aspect of the present invention, there is provided a nonreciprocal transmission line apparatus configured by connecting in cascade at least one unit cell. Each of the unit cell(s) includes: (a) a microwave transmission line section; (b) a series branch circuit equivalently including a capacitance element; and (c) first and second parallel branch circuits provided branched from the transmission line section, each of the first and second parallel branch circuit equivalently including an inductive element between first and second ports. A propagation constant in a forward direction and a propagation constant in a backward direction of the nonreciprocal transmission line apparatus are different from each other. The transmission line section of each unit cell has spontaneous magnetization so as to have gyro anisotropy by being magnetized in a direction different from a propagation direction of microwaves or by being externally magnetized by an external magnetic field. The first parallel branch circuit is a first stub conductor having a first electrical length, and the second parallel branch circuit is a second stub conductor having a second electrical length shorter than the first electrical length. When a phase constant in a first mode of propagation in the forward direction is β_p, and a phase constant in a second mode of propagation in the backward direction is β_m, the first and second electrical lengths are set so that a function of nonreciprocal phase shift amount $\beta_{NR}=(\beta_p-\beta_m)/2$ with respect to the operating angular frequency comes close to a function of nonreciprocal phase shift amount β_{NRZ} with respect to an operating angular frequency, when beam squint of such a phenomenon that a radiation direction of electromagnetic waves radiated from the nonreciprocal transmission line apparatus changes in accordance with frequency does not occur in the vicinity of an intersection of a dispersion curve representing a relation between the phase constant β_p and the operating angular frequency and a dispersion curve representing a relation between the phase constant β_m, and the operating angular frequency.

In the nonreciprocal transmission line apparatus of the first aspect of the present invention, the function is a function proportional to the operating angular frequency.

In addition, in the nonreciprocal transmission line apparatus of the first aspect of the present invention, the first stub conductor has a first admittance, the second stub conductor has a second admittance, and the first and second electrical lengths are set such that: (a) the first admittance substantially coincides with the second admittance at a predetermined operating angular frequency lower than the operating angular frequency at the intersection, and (b) respective imaginary parts of the first and second admittances are negative at the predetermined operating angular frequency.

Further, in the nonreciprocal transmission line apparatus of the first aspect of the present invention, the first stub conductor is a short-circuit stub, and the first electrical length is set to be longer than one-half of a guide wavelength. The second stub conductor is a short-circuit stub, and the second electrical length is set to be shorter than one-fourth of the guide wavelength.

Furthermore, in the nonreciprocal transmission line apparatus of the first aspect of the present invention, the first stub conductor is an open stub, and the first electrical length is set to be longer than one-fourth of a guide wavelength. The second stub conductor is a short-circuit stub, and the second electrical length is set to be shorter than one-fourth of the guide wavelength.

Furthermore, the nonreciprocal transmission line apparatus of the first aspect of the present invention further includes a grounding conductor provided between the first stub conductors, and the grounding conductor provides a shield between the first stub conductors.

According to the second aspect of the present invention, there is provided an antenna apparatus including the nonreciprocal transmission line apparatus of the first aspect of the present invention.

Advantageous Effects of the Invention

According to the nonreciprocal transmission line apparatus and the antenna apparatus of the present invention, the function of the nonreciprocal phase shift amount $\beta_{NR}=(\beta_p-\beta_m)/2$ with respect to the operating angular frequency is configured so as to come close to the function of the nonreciprocal phase shift amount β_{NR} with respect to the operating angular frequency when the beam squint of such a phenomenon that the radiation direction of electromagnetic waves radiated from the nonreciprocal transmission line apparatus changes in accordance with the frequency does not occur. Therefore, any beam squint does not substantially occur in the vicinity of the center frequency of the operation band.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an equivalent circuit diagram of a unit cell **60**A of a transmission line of a first example in a nonreciprocal transmission line apparatus according to an embodiment of the present invention;

FIG. **2** is an equivalent circuit diagram of a unit cell **60**B of a transmission line of a second example in a nonreciprocal transmission line apparatus according to an embodiment of the present invention;

FIG. **3** is an equivalent circuit diagram of a unit cell **60**C of a transmission line of a third example in a nonreciprocal transmission line apparatus according to an embodiment of the present invention;

FIG. **4** is an equivalent circuit diagram of a unit cell **60**D of a transmission line of a fourth example in a nonreciprocal transmission line apparatus according to an embodiment of the present invention;

FIG. **5** is a graph showing dispersion curves in the case of an unbalanced state in a prior art reciprocal transmission line apparatus;

FIG. **6** is a graph showing dispersion curves in the case of a balanced state in a prior art reciprocal transmission line apparatus;

FIG. **7** is a graph showing dispersion curves in the case of an unbalanced state in a nonreciprocal transmission line apparatus according to an embodiment;

FIG. **8** is a graph showing dispersion curves in the case of a balanced state in a nonreciprocal transmission line apparatus according to an embodiment;

FIG. **9** is a block diagram showing a configuration of a nonreciprocal transmission line apparatus **70**A configured by connecting in cascade the unit cells **60**A of FIG. **1**;

FIG. **10** is a block diagram showing a configuration of a nonreciprocal transmission line apparatus **70**B configured by connecting in cascade the unit cells **60**B of FIG. **2**;

FIG. **11** is a block diagram showing a configuration of a nonreciprocal transmission line apparatus **70**C configured by connecting in cascade the unit cells **60**C of FIG. **3**;

FIG. **12** is a block diagram showing a configuration of a nonreciprocal transmission line apparatus **70**D configured by connecting in cascade the unit cells **60**D of FIG. **4**;

FIG. **13**A is a perspective view showing a configuration of a nonreciprocal transmission line apparatus **70**E according to an embodiment of the present invention;

FIG. **13**B is a perspective view showing a configuration of a nonreciprocal transmission line apparatus **70**E according to a modified embodiment of the present invention;

FIG. **14** is a longitudinal sectional view of a ferrite square bar **15**A in a nonreciprocal line section NRS of FIG. **13**A;

FIG. **15** is a perspective view showing a configuration of a nonreciprocal transmission line apparatus **70**G according to a comparative example;

FIG. **16** is a graph showing dispersion curves of the nonreciprocal transmission line apparatus **70**G of FIG. **15**, and showing simulation calculated values of frequency characteristics of the nonreciprocal phase shift amount β_{NR};

FIG. **17** is a graph showing dispersion curves of the nonreciprocal transmission line apparatus **70**E of FIG. **13**A, and showing simulation calculated values of the frequency characteristics of the nonreciprocal phase shift amount β_{NR};

FIG. **18** is a plan view showing a concrete configuration of the nonreciprocal transmission line apparatus **70**E of FIG. **13**A;

FIG. **19** is a graph showing dispersion curves of the nonreciprocal transmission line apparatus **70**E of FIG. **13**A, showing simulation calculated values of the frequency characteristics of the nonreciprocal phase shift amount β_{NR}, and showing experimental values when the nonreciprocal transmission line apparatus **70**E of FIG. **13**A is formed in a manner similar to that of FIG. **18**;

FIG. **20**A is a perspective view showing a configuration of a nonreciprocal transmission line apparatus **70**F according to a modified embodiment of the present invention;

FIG. **20**B is a perspective view showing a configuration of a modified embodiment of the nonreciprocal transmission line apparatus **70**F of FIG. **20**A;

FIG. **21** is a graph showing dispersion curves of the nonreciprocal transmission line apparatus **70**F of FIG. **20**A, and showing simulation calculated values of the frequency characteristics of the nonreciprocal phase shift amount β_{NR};

FIG. **22** is an enlarged view of FIG. **21**;

FIG. **23** is a plan view schematically showing a configuration of the nonreciprocal transmission line apparatus **70**F when the stub conductors **13**A of FIG. **20**A are open stubs;

FIG. **24** is a graph showing an operating angular frequency dependence of admittances Y_1 and Y_2 in the nonreciprocal transmission line apparatus **70**F of FIG. **23** and a frequency dependence of the nonreciprocal phase shift amount β_{NR};

FIG. **25** is a plan view showing a concrete configuration used for the simulation of the nonreciprocal transmission line apparatus **70**F of FIG. **20**A;

FIG. **26** is a perspective view of the nonreciprocal transmission line apparatus **70**F of FIG. **25**;

FIG. **27** is a graph showing dispersion curves of the nonreciprocal transmission line apparatus **70**F of FIG. **25**, and showing simulation calculated values of the frequency characteristics of the nonreciprocal phase shift amount β_{NR};

FIG. **28** is a graph showing radiation characteristics of the nonreciprocal transmission line apparatus **70**F of FIG. **25**;

FIG. **29** is a graph showing frequency characteristics of the radiation angle θ of the nonreciprocal transmission line apparatus **70**F of FIG. **25**;

FIG. **30** is a graph showing frequency characteristics of the radiant gain of the nonreciprocal transmission line apparatus **70**F of FIG. **25**;

FIG. **31**A is a perspective view showing a configuration of a pseudo traveling wave resonant antenna apparatus that uses the nonreciprocal transmission line apparatus **70**F of FIG. **25**;

FIG. **31**B is a graph of numerical calculation results of the pseudo traveling wave resonant antenna apparatus of FIG. **31**A, showing frequency characteristics of a reflection coefficient S_{11} when the pseudo traveling wave resonant antenna apparatus is viewed from a feed line F;

FIG. **31**C is a graph of numerical calculation results of the pseudo traveling wave resonant antenna apparatus of FIG. **31**A, showing a magnetic field distribution along a longitudinal direction of the nonreciprocal transmission line apparatus **70**F and a normalized amplitude of the electric field distribution;

FIG. **31**D is a graph of numerical calculation results of the pseudo traveling wave resonant antenna apparatus of FIG. **31**A, showing a phase gradient of the magnetic field distribution along the longitudinal direction of the nonreciprocal transmission line apparatus **70**F;

FIG. **31**E is a graph of numerical calculation results of the pseudo traveling wave resonant antenna apparatus of FIG. **31**A, showing frequency characteristics of a radiation beam angle in a broad side direction of the pseudo traveling wave resonant antenna apparatus;

FIG. **31**F is a graph of numerical calculation results of the pseudo traveling wave resonant antenna apparatus of FIG. **31**A, showing a radiation pattern on a plane that includes the longitudinal direction of the pseudo traveling wave resonant antenna apparatus and a normal of a substrate;

FIG. **32**A is a photograph showing a trial manufacture example of the pseudo traveling wave resonant antenna apparatus of FIG. **31**A;

FIG. **32**B is a graph of experimental results of the pseudo traveling wave resonant antenna apparatus of the trial manufacture example of FIG. **32**A, showing a frequency characteristics of the radiation beam angle in the broad side direction of the pseudo traveling wave resonant antenna apparatus; and

FIG. **32**C is a graph of experimental results of the pseudo traveling wave resonant antenna apparatus of the trial manufacture example of FIG. **32**A, showing a radiation pattern on a plane that includes a longitudinal direction of a pseudo traveling wave resonant antenna apparatus and a normal of a substrate.

BEST MODE FOR CARRYING OUT THE INVENTION

Embodiments of the present invention will be described below with reference to the drawings. In the following embodiments, like components are denoted by the same reference signs.

First of all, a fundamental configuration and an operation principle of the nonreciprocal transmission line apparatuses **70**A to **70**F according to the present invention are described below with reference to FIGS. **1** to **12**. Mathematical expressions indicated in the present specification are respectively identified by parenthesized numbers each positioned after a mathematical expression.

A nonreciprocal transmission line apparatus according to an embodiment of the present invention is configured by connecting in cascade a plurality of unit cells of a transmission line. FIGS. **1** to **4** are equivalent circuit diagrams of unit cells **60**A to **60**D of exemplary transmission lines, each used as a nonreciprocal transmission line apparatus according to a first embodiment of the present invention. Each of the unit cells **60**A to **60**D is configured to include a transmission line part having a nonreciprocal phase shift characteristic of forward and backward propagation constants different from each other, and is configured such that a capacitive element is equivalently inserted in a series branch circuit and an inductive element is equivalently inserted in a shunt branch circuit (See FIGS. **1** to **4**). The circuit or apparatus, to which the configuration of the nonreciprocal transmission line apparatus according to the present invention can be applied, includes: printed board circuits, waveguides, and dielectric lines for use in microwave, millimeter wave, sub-millimeter wave, or terahertz wave, such as strip lines, microstrip lines, slot lines, and coplanar lines; and further includes: all sorts of configurations supporting a waveguide mode or an evanescent mode, including plasmon, polariton, magnon, or the like; combinations thereof; and free spaces capable of being considered as their equivalent circuit. Electromagnetic waves transmitted by the nonreciprocal transmission line apparatus include microwaves, millimeter waves, quasi-millimeter waves, and terahertz waves in the frequency bands of the UHF (Ultra High Frequency) band or higher, and in the present specification, these electromagnetic waves are collectively referred to as a “microwave”.

The transmission line having the nonreciprocal phase shift characteristics is configured by including such a transmission line among the aforementioned transmission lines that is configured to particularly include gyrotropic materials in part or as a whole, and to be magnetized in a magnetization direction different from a propagation direction of the electromagnetic wave (more preferably, in a direction orthogonal to the propagation direction) to be asymmetric with respect to a plane composed of the propagation direction and the magnetization direction. In addition to such a transmission line, a lumped-parameter element, having an equivalent nonreciprocal phase shift feature and being sufficiently small as compared to a wavelength, is also available as a transmission line having the nonreciprocal phase shift characteristics. The gyrotropic materials include all such materials that a dielectric constant tensor, a permeability tensor, or both of them exhibits gyrotropy, due to spontaneous magnetization, magnetization produced by an externally supplied DC or low-frequency magnetic field, or an orbiting free charge. Exemplary and specific gyrotropic materials include: ferrimagnetic materials such as ferrite, ferromagnetic materials, solid-state plasma (semiconductor materials etc.), liquid and gaseous plasma media, and magnetic artificial media made by micromachining or the like, for use in microwave, millimeter wave, and so on.

The capacitive element inserted in the series branch circuit may include a capacitor commonly used in electric circuits, a distributed-parameter capacitance element for microwave, millimeter wave, etc., and may include equivalent circuits or circuit elements having a negative effective permeability for the electromagnetic wave mode of propagation through the transmission line. In order to obtain the negative effective permeability, the series branch circuit should be equivalent to a transmission line dominantly operating as a capacitive element. Concrete examples of elements having the negative effective permeability include: a split ring resonator made of metal; a spatial arrangement including at least one magnetic resonator of a spiral structure; a spatial arrangement of a magnetically resonating dielectric resonator; or a microwave circuit operable in the waveguide mode or the evanescent mode having the negative effective permeability, such as an edge mode propagation along a ferrite substrate microstrip line. In addition, the capacitive element inserted in the series branch circuit may be a series or parallel connection of capacitive elements and inductive elements, or a combination of their series and parallel connections. The element or circuit to which to be inserted may be capacitive as a whole.

The inductive element inserted in the shunt branch circuit may include a lumped-parameter element such as a coil used in electrical circuits, and a distributed-parameter inductive element such as a short-circuit stub conductor for microwave, millimeter wave, etc., and may include a circuit or an element having a negative effective dielectric constant for the electromagnetic wave mode of propagation through the transmission line. In order to obtain the negative effective dielectric constant, the shunt branch circuit should be equivalent to a transmission line dominantly operating as an inductive element. Concrete examples of elements having the negative effective dielectric constant include: a spatial arrangement including at least one electric resonator of a metal thin wire, a metal sphere, etc.; a spatial arrangement of an electrically resonating dielectric resonator other than metal; or a microwave circuit operable in a waveguide mode or an evanescent mode having the negative effective dielectric constant, such as waveguides and parallel planar lines, in which the TE mode is in a blocking region. In addition, the inductive element inserted in the shunt branch circuit may be a series or parallel connection of capacitive elements and inductive elements, or a combination of their series and parallel connections. The element or circuit to which to be inserted may be inductive as a whole.

The evanescent mode may occur in the transmission line apparatus having the nonreciprocal phase shift characteristics, when the transmission line apparatus has the negative effective permeability for the electromagnetic wave mode of propagation through the transmission line apparatus. Since the negative effective permeability corresponds to a case where a capacitive element is inserted in the series branch circuit, the equivalent circuit of the transmission line apparatus includes both the nonreciprocal phase shift part and the series capacitive element part.

The evanescent mode may occur in the transmission line apparatus having the nonreciprocal phase shift characteristics, when the transmission line apparatus has the negative effective dielectric constant for the electromagnetic wave mode of propagation through the transmission line apparatus. Since the negative effective dielectric constant corresponds to a case where an inductive element is inserted in the shunt branch circuit, the equivalent circuit of the transmission line apparatus includes both the nonreciprocal phase shift part and the shunt inductive element part.

FIGS. **1** and **2** show cases where the unit cells **60**A and **60**B have an asymmetric T-structure and an asymmetric π-structure, respectively. FIGS. **3** and **4** show more simple cases where the unit cells **60**C and **60**D have a symmetric T-structure and a symmetric π-structure, respectively. Hereinafter, it is assumed in principle that the transmission line length of the unit cells **60**A to **60**D (i.e., the period length p=p**1**+p**2**) is sufficiently small with respect to the wavelength. Therefore, essentially the same result will be obtained for any of the T-structure, the π-structure, or L-structure, in a manner similar to that of the case of unit cells of a transmission line in the conventional composite right/left-handed transmission line apparatus. In fact, the L-structure falls under the case of FIG. **1** or **2** with parameters being set appropriately. It is emphasized that the transmission line length of each of the unit cells **60**A to **60**D with respect to the wavelength does not restrict the fundamental operation described here.

FIGS. **1** to **4** show simple line structures, where a transmission line includes two transmission line parts **61** and **62** having predetermined line lengths (the transmission line lengths of FIGS. **1** and **2** are p**1** and p**2**, respectively, and each of the transmission line lengths of FIGS. **3** and **4** is p/2), a capacitive element or a capacitive circuit network is inserted in the series branch circuit of the transmission line, and an inductive element or an inductive circuit network is inserted in the shunt branch circuit of the transmission line. FIG. **1** shows capacitors C**1** and C**2** and an inductor L inserted in the transmission line, in order to simply and collectively represent the effective values of these elements. Similarly, FIG. **2** shows a capacitor C and inductors L**1** and L**2** inserted in the transmission line. Each of the transmission line parts **61** and **62** is configured to have a nonreciprocal phase shift characteristic of different forward and backward

propagation constants. When considering the propagation constants in the present specification, the imaginary part of the propagation constants, i.e., the phase constant is used. As parameters indicative of the nonreciprocity of the transmission line part **61**, β_{Np1} and Z_{p1} denote a forward phase constant and a forward characteristic impedance ("forward" means a direction from a port P**11** to a port P**12**), respectively, and β_{Nm1} and Z_{m1} denote a backward phase constant and a backward characteristic impedance ("backward" means a direction from the port P**12** to the port P**11**), respectively. Similarly, as parameters indicative of the nonreciprocity of the transmission line part **62**, β_{Np2} and Z_{p2} denote a forward phase constant and a forward characteristic impedance, respectively, and β_{Nm2} and Z_{m2} denote a backward phase constant and a backward characteristic impedance, respectively. Each of the transmission lines of FIGS. **1** and **2** has asymmetric transmission line parts **61** and **62**. On the other hand, each of the transmission lines of FIGS. **3** and **4** has symmetric transmission line parts **61** and **62**, and satisfies: p**1**=p**2**=p/2, $\beta_{Np1}=\beta_{Np2}=\beta_{Np}$, $\beta_{Nm1}=\beta_{Nm2}=\beta_{Nm}$, $Z_{p1}=Z_{p2}=Z_p$, $Z_{m1}=Z_{m2}=Z_m$. In addition, a transmission line of T-structure satisfy C**1**=C**2**=C, and a transmission line of π-structure satisfy L**1**=L**2**=L. Specifically, by imposing periodic boundary conditions to both ends of the unit cells **60**A to **60**D of the transmission lines of FIGS. **3** and **4**, the following equation is obtained:

$$\cos\left[\left(\beta-\frac{\Delta\beta}{2}\right)-p\right]=\left(1-\frac{1}{\omega^2\cdot L\cdot C}\cdot\frac{Z_p\cdot Z_m}{(Z_p+Z_m)^2}\right)\cdot\cos(\overline{\beta}\cdot p)+\frac{1}{Z_p+Z_m}\left(\frac{Z_p\cdot Z_m}{\omega\cdot L}+\frac{1}{\omega\cdot C}\right)\cdot\sin(\overline{\beta}\cdot p)-\frac{1}{2\cdot\omega^2\cdot L\cdot C}\cdot\frac{Z_p^2+Z_m^2}{(Z_p+Z_m)^2} \tag{1}$$

$\Delta\beta$ and $\overline{\beta}$ are given as follows:

$$\Delta\beta=\beta_{Np}-\beta_{Nm},\ \text{and}$$

$$\overline{\beta}=\frac{\beta_{Np}+\beta_{Nm}}{2},$$

where ω denotes an operating angular frequency, and β denotes a phase constant of an electromagnetic wave propagating along a periodic structure. The Equation (1) denotes a relation between the operating angular frequency ω and the phase constant β, and therefore, it is an equation of dispersion (ω-β diagram).

Assuming the reciprocal characteristic ($\beta_{Np}=\beta_{Nm}$, and $Z_p=Z_m$) in the Equation (1), the transmission line becomes the same as the conventional reciprocal transmission line apparatus, and the Equation (1) is simplified as follows:

$$\cos(\beta\cdot p)=\cos(\beta_{Np}\cdot p)-\frac{1}{2\cdot\omega^2\cdot L\cdot C}\cdot\cos^2\left(\frac{\beta_{Np}\cdot p}{2}\right)+\frac{j}{2}\cdot\left(\frac{Y}{Y_p}+\frac{Z}{Z_p}\right)\cdot\sin(\beta_{Np}\cdot p). \tag{2}$$

It is assumed that in the Equation (2), the admittance Y=1/jωL, and the impedance Z=1/jωC.

FIG. **5** is a graph showing dispersion curves of a conventional reciprocal transmission line apparatus in an unbalanced state. FIG. **6** is a graph showing dispersion curves of the conventional reciprocal transmission line apparatus in a balanced state. The graphs of FIGS. **5** and **6** indicate characteristics of an angular frequency ω versus a normalized phase constant β·p/π FIG. **5** shows typical dispersion curves in the case of the conventional transmission line apparatus denoted by the Equation (2), and in general, a forbidden band appears between a band with the right-handed (RH) transmission characteristic and a band with the left-handed (LH) transmission characteristic. Frequencies at the upper limit of the left-handed transmission band at the lower limit of the right-handed transmission band are obtained as the solutions of a quadratic equation of the angular frequency ω^2, by imposing the condition of the phase constant β=0 on the Equation (2). As a result, the following two solutions are obtained:

$$\omega_1 = \sqrt{\frac{1}{L \cdot \varepsilon_p \cdot p}}, \text{ and} \tag{3}$$

$$\omega_2 = \sqrt{\frac{1}{C \cdot \mu_p \cdot p}}, \tag{4}$$

where ϵ_p and μ_p denote an effective dielectric constant and an effective permeability of the transmission line parts **61** and **62** in the unit cells **60**A to **60**D. Therefore, in order for the cutoff frequencies to satisfy $\omega_1=\omega_2$ with no forbidden band, it is only necessary for the Equation (2) to have a multiple root under the condition of the phase constant β=0, and as a result, the following equation is obtained:

$$Z_p = \sqrt{\frac{\mu_p}{\varepsilon_p}} = \sqrt{\frac{L}{C}}. \tag{5}$$

According to the results of the Equation (5), no gap appears if an impedance $\sqrt{L/C}$ of the capacitor C and the inductor L is identical to the characteristic impedances Z_p of the transmission line parts **61** and **62**, where the capacitor C is a capacitive element inserted in the series branch circuit, and the inductor L is an inductive element inserted in the shunt branch circuit. The Equation (5) is a kind of condition for impedance matching. FIG. **6** shows dispersion curves of that case.

The dispersion curves of the nonreciprocal transmission line apparatus given by the Equation (1) is described below. In the case of the reciprocal transmission line, it is shown according to the Equation (2) that the dispersion curves are symmetric with respect to the axis of the phase constant β=0 (i.e., ω axis). On the other hand, in the case of the nonreciprocal transmission line apparatus, it is readily shown according to the left side of the Equation (1) that the axis of symmetry of the dispersion curves is shifted with respect to β in the positive direction from the axis of β=0 by the following equation:

$$\beta_{NR} = \frac{\Delta\beta}{2} = \frac{\beta_{Np} - \beta_{Nm}}{2}. \tag{6}$$

β_{NR} is referred to as a nonreciprocal shift amount hereinafter. As a result, FIG. **7** is obtained corresponding to FIG. **5**.

FIG. **7** is a graph showing dispersion curves of a nonreciprocal transmission line apparatus according to the embodiment in an unbalanced state. FIG. **8** is a graph showing dispersion curves of the nonreciprocal transmission line apparatus according to the embodiment in a balanced state.

As described above, the nonreciprocal transmission line apparatus is significantly different from the reciprocal transmission line apparatus such that the axis of symmetry of the dispersion curves is shifted from the ω axis in the right or left direction, because the phase constant $\beta=\beta_p$ in the forward direction and the phase constant $\beta=\beta_m$ satisfy $\beta_m \neq \beta_p$ (therefore, the forward and backward propagation constants are different from each other), i.e., because of the effect of a nonreciprocal phase shift. It is to be noted that the nonreciprocal shift amount β_{NR} can be represented by the following equation, using the phase constant β_p in the forward direction and the phase constant β_m in the backward direction instead of the Equation (6):

$$\beta_{NR} = \frac{\Delta\beta}{2} = \frac{\beta_p - \beta_m}{2}.$$

As a result, the transmission bands are classified into the following five transmission bands (A) to (E).

(A) Both the forward and backward propagations are done as a left-handed transmission. The magnitudes of the propagation constants are different from each other.

(B) The forward propagation is done as a left-handed transmission, and the backward propagation has zero propagation constant and infinite guide wavelength.

(C) The forward propagation is done as a left-handed transmission, and the backward propagation is done as the right-handed transmission.

(D) The forward propagation is done as a right-handed transmission, and the backward propagation has zero propagation constant and infinite guide wavelength.

(E) Both the forward and backward propagations are done as a right-handed transmission. The magnitudes of the propagation constants are different from each other.

In general, a stop band (forbidden band) appears at the center of the transmission band (C) as shown from FIG. **7**. In particular, when using the transmission band indicated by RH/LH of FIGS. **7** and **8**, there is such an advantageous feature that even if supplying microwave signals to both the ports in both directions (the forward and backward directions), the flows of phases have an identical direction in the left-handed transmission and right-handed transmission.

Considering the conventional reciprocal transmission line for the purpose of comparison, the two identical modes with positive and negative directions of the power transmission intersect each other without coupling between these two modes, when the matching condition of the Equation (5) is satisfied, i.e., when the phase constant β=0 as shown in FIG. **6**. Similarly, on the axis of symmetry $\beta=\Delta\beta/2=\beta_{NR}$ of the dispersion curves of the Equation (1), the Equation (1) is a quadratic equation with respect to the angular frequency ω^2. By imposing a condition of a multiple root in order to avoid a band-gap, the following equation is obtained:

$$Z_p = \sqrt{\frac{\mu_p}{\varepsilon_p}} = \sqrt{\frac{L}{C}}, \tag{7}$$

or

$$Z_m = \sqrt{\frac{\mu_m}{\varepsilon_m}} = \sqrt{\frac{L}{C}},$$

where ϵ_p and μ_p denote a forward effective dielectric constant and a forward effective permeability of the nonreciprocal transmission line parts **61** and **62** in the unit cells **60**A to **60**D, and ϵ_m and μ_m denote their backward effective dielectric constants and backward effective permeabilities. According to the Equation (7), the condition for avoiding a gap near the intersection of the two modes is a condition for impedance matching, in a manner similar to that of the case of the Equation (5) of the reciprocal transmission line apparatus. In addition, it is only necessary to insert an inductor L and a capacitor C so that matching is made in either the forward direction or the backward direction, and there is an advantageous feature that a weaker condition of impedance matching is imposed than in the case of the reciprocal transmission line apparatus.

A more general case of two asymmetric transmission line parts **61** and **62** as shown in FIGS. **1** and **2** is described below. Even in such an asymmetric case, its fundamental operation depends on dispersion curves similar to those shown in FIGS. **7** and **8**. The position of the axis of symmetry is modified as follows on the normalized phase constant $\beta \cdot p/\pi$ of the horizontal axes of FIGS. **7** and **8**:

$$\frac{\beta \cdot p}{\pi} = \frac{(\beta_{Np1} - \beta_{Nm1}) \cdot p_1}{2\pi} + \frac{(\beta_{Np2} - \beta_{Nm2}) \cdot p_2}{2\pi}.$$

Moreover, when the two nonreciprocal transmission line parts **61** and **62** have an identical propagation characteristic, a matching condition for avoiding a band-gap is the same as that of the Equation (7). It is noted that the condition of FIG. **1** is as follows:

$$\frac{1}{C} = \frac{1}{C1} + \frac{1}{C2},$$

and the condition of FIG. **2** is as follows:

$$\frac{1}{L} = \frac{1}{L1} + \frac{1}{L2}.$$

Referring to FIGS. **9** to **12**, an entire nonreciprocal transmission line apparatus according to an embodiment of the present invention is configured by including at least one or more of the plurality of unit cells **60**A to **60**D of FIGS. **1** to **4**, and by connecting them in cascade. FIG. **9** is a block diagram showing a configuration of a nonreciprocal transmission line apparatus **70**A including a cascade connection of a plurality of the unit cells **60**A of FIG. **1**. Referring to FIG. **9**, the nonreciprocal transmission line apparatus **70**A is configured by connecting in cascade the plurality of unit cells **60**A between the port P**1** and the port P**2**. FIG. **10** is a block diagram showing a configuration of a nonreciprocal transmission line apparatus **70**B including a cascade connection of a plurality of the unit cells **60**B of FIG. **2**. Referring to FIG. **10**, the nonreciprocal transmission line apparatus **70**B is configured by connecting in cascade the plurality of unit cells **60**B between the port P**1** and the port P**2**. FIG. **11** is a block diagram showing a configuration of a nonreciprocal transmission line apparatus **70**C including a cascade connection of a plurality of the unit cells **60**C of FIG. **3**. Referring to FIG. **11**, the nonreciprocal transmission line apparatus **70**C is configured by connecting in cascade the plurality of unit cells **60**C between the port P**1** and the port P**2**. FIG. **12** is a block diagram showing a configuration of a nonreciprocal transmission line apparatus **70**D including a cascade connection of a plurality of the unit cells **60**D of FIG. **4**. Referring to FIG. **12**, the nonreciprocal transmission line apparatus **70**D is configured by connecting in cascade the plurality of unit cells **60**D between the port P**1** and the port P**2**. Even when cascade connecting a plurality of unit cells **60**A to **60**D, it is not necessary to configure the nonreciprocal transmission line apparatus from only one type of the unit cells **60**A to **60**D, and it is possible to cascade connect a combination of different types of the unit cells **60**A to **60**D.

Hereinafter, the dispersion curves of the nonreciprocal transmission line apparatuses **70**A to **70**F according to the present embodiment and the following embodiments are dispersion curves in the balanced state as shown in FIG. **8**. Moreover, in the dispersion curves of FIG. **8**, the operating angular frequency ω at the intersection where two modes intersect each other is defined as the center angular frequency ω_C, and the nonreciprocal phase shift amount β_{NR} at the intersection is defined as a nonreciprocal phase shift amount β_{NRC}. It is also operable in the case of the dispersion curves in an unbalanced state where a band-gap exists as shown in FIG. **7**. In this case, the angular frequency corresponding to the center operating angular frequency ω_C in FIG. **8**, which also depends on the transmission line terminal conditions on both sides of the transmission line, corresponds to two angular frequencies ωc_U and ωc_L corresponding to the band-gap ends of the dispersion curves of FIG. **7** or inside the band-gap between them.

When the nonreciprocal transmission line apparatus **70**A to **70**F are formed on a dielectric substrate, the derivative of an angle θ (hereinafter, referred to as a radiation angle θ) between the beam direction of the pseudo traveling wave resonator antenna apparatus having the nonreciprocal transmission line apparatus **70**A to **70**F and the direction perpendicular to the dielectric substrate with respect to of the operating angular frequency ω is expressed by the following equation in the vicinity of the center angular frequency ω_C (See Non-Patent Document 1):

$$\frac{d\theta}{d\omega} \cong \frac{1}{\sqrt{\beta_0^2 - \beta_{NRC}^2}} \left(\left. \frac{d\beta_{NR}}{d\omega} \right|_{\omega=\omega_C} - \frac{\beta_{NRC}}{\omega_C} \right) \tag{8}$$

where β_0 denotes a phase constant of electromagnetic waves in vacuum. Therefore, in order to prevent the beam squint of such a phenomenon that the radiation angle θ of the electromagnetic waves radiated from the nonreciprocal transmission line apparatuses **70**A to **70**B changes in accordance with the operating frequency from occurring in the vicinity of the center angular frequency ω_C in the pseudo traveling wave resonator antenna apparatus having the nonreciprocal transmission line apparatus **70**A to **70**F, the following equation is only required to hold:

$$\beta_{NRC} = \left. \frac{d\beta_{NR}}{d\omega} \right|_{\omega=\omega_C} \times \omega \tag{9}$$

That is, the nonreciprocal phase shift amount β_{NR} is required to be proportional to the operating angular frequency ω in the vicinity of the center angular frequency ω_C. The nonreciprocal transmission line apparatuses **70**A to **70**F of the present embodiment and the following embodiments are configured so as to satisfy the Equation (9), and this leads to that the occurrence of the beam squint can be prevented.

FIG. **13**A is a perspective view showing a configuration of a nonreciprocal transmission line apparatus **70**E according to an embodiment of the present invention. The XYZ coordinates shown in FIG. **13**A are referred to for the sake of explanation. Referring to FIG. **13**A, the nonreciprocal transmission line apparatus **70**E is configured to include a grounding conductor **11** provided parallel to the XY plane, a ferrite square bar (ferrite rod) **15**A extending along the Y axis on the grounding conductor **11**, a dielectric substrate **10** provided on both the +X and −X sides of the ferrite square bar **15**A on the grounding conductor **11**, a strip conductor **12**, stub conductors **13**A, stub conductors **13**B, and capacitors Cse. Moreover, the ferrite square bar **15**A, the strip conductor **12**, the stub conductors **13**A, the stub conductors **13**B and the capacitors Cse configure a microstrip line **12**E extending between ports P**1** and P**2** along the Y axis. A microwave signal is supplied from the port P**1** or P**2**.

The ferrite square bar **15**A is magnetized in a magnetization direction different from the propagation direction of electromagnetic waves, and has spontaneous magnetization so as to have gyro anisotropy. In FIG. **22**, the saturation magnetization M_S and the internal magnetic field H_0 of the ferrite square bar **15**A are indicated by arrows. In this case, the magnetization direction should be preferably a direction (e.g., +Z direction) orthogonal to the propagation direction (direction along the Y axis) of electromagnetic waves. It is acceptable to use a ferrite square bar having no spontaneous magnetization and apply a magnetic field by the external magnetic field generator **80** of FIG. **13**B in place of the ferrite square bar **15**A having a spontaneous magnetization.

Referring to FIG. **13**A, the microstrip line **12**E is configured by connecting in cascade the unit cells **60**E of the transmission line having a period length p. One of the unit cells **60**E is described. Each unit cell **60**E is configured to include the strip conductor **12** extending along the Y axis on the ferrite square bar **15**A, the capacitor Cse, and the stub conductors **13**A and **13**B. The capacitor Cse is connected to the end portion on the +Y side of the strip conductor **12**, and the capacitor Cse is further connected to the strip conductor **12** of the unit cell **60**E being ad adjacent to the +Y side of the unit cell **60**A. Therefore, each capacitor Cse is inserted in series in the microstrip line **12**E. Referring to FIG. **13**A, capacitors, each having a capacitance **2**Cse that is double one of the capacitor Cse forming between the strip conductors **12**, are inserted at both ends of the microstrip line **12**E.

The stub conductor **13**A has an electrical length La, and extends on the −X side of the strip conductor **12**. On the other hand, the stub conductor **13**B has an electrical length Lb shorter than the electrical length La, and extends on the +X side of the strip conductor **12**. The stub conductors **13**A and **13**B each diverge from the strip conductor **12**, and are provided as two parallel branch circuits corresponding to the inductor L (parallel branch circuit) of FIG. **1**. In detail, the stub conductor **13**A extends in the −X direction along the X axis of the dielectric substrate **10**, where its one end is connected to the strip conductor **12**, and its other end is short-circuited (short-circuit stub) to the grounding conductor **11** via a grounding conductor **17**A at the end portion on the −X side of the dielectric substrate **10**. Likewise, the stub conductor **13**B extends in the +X direction along the X axis on the dielectric substrate **10**, where its one end is connected to the strip conductor **12**, and its other end is short-circuited to the grounding conductor **11** via a grounding conductor **17**B at the end portion on the +X side of the dielectric substrate **10**.

As described above, the stub conductors **13**A and **13**B are formed on mutually different sides with respect to a plane (YZ plane) formed of the propagation direction (e.g., +Y direction or −Y direction which is indicated by an arrow on the microstrip line **12**E of FIG. **13**A) and the magnetization direction (e.g., +Z direction) of the microstrip line **12**E. Each of the stub conductors **13**A and **13**B functions as an inductive element. The equivalent circuit of the unit cell **60**E configured as mentioned above is similar to the equivalent circuit of the unit cell **60**A of FIG. **1**.

The nonreciprocal transmission line apparatus **70**E of FIG. **13**A is utilized for achieving a leaky wave antenna of resonance type. As described above, the nonreciprocal transmission line apparatus **70**E is configured of the microstrip line **12**E, which is provided between the ports P**1** and P**2**, and in which the ferrite square bar **15**A is embedded. Further, the stub conductors **13**A and **13**B of strip conductors, and the capacitor Cse are periodically inserted at an interval of a period length p in the microstrip line **12**E. Since the major mode of the nonreciprocal transmission line apparatus **70**E is the edge guide mode and the stub conductors **13**A and **13**B are asymmetrically inserted in the transmission line, the nonreciprocal transmission line apparatus **70**E exhibits nonreciprocal transmission characteristics.

In concrete, when the impedances (i.e., electrical lengths) of the stub conductors **13**A and **13**B are made to be different from each other, the structure of the nonreciprocal transmission line apparatus **70**E becomes asymmetrical with respect to the plane (YZ plane) formed of the propagation direction and the magnetization direction of the microstrip line **12**E. Consequently, the propagation constant in the forward direction (direction from port P**1** to P**2**) and the propagation constant in the backward direction (direction from port P**2** to P**1**) are different from each other, so that a state of propagation in the right-handed mode in the forward direction and propagation in the left-handed mode in the backward direction can be achieved. According to this configuration, the magnitude of nonreciprocity can be changed by adjusting the electrical lengths La and Lb of the stub conductors **13**A and **13**B, respectively. As described in detail later, the electrical lengths La and Lb of the stub conductors **13**A and **13**B are set so that any beam squint does not substantially occur in the antenna apparatus using the nonreciprocal transmission line apparatus **70**E.

The propagation characteristic in the TE mode of propagation along the microstrip line **12**E, in which the ferrite square bar **15**A is embedded, changes depending on the boundary conditions on the side surfaces on both sides of the microstrip line **12**E. The inventor and others of the present application analyzed the general nonreciprocal dispersion characteristic of the nonreciprocal transmission line apparatus **70**E. In the nonreciprocal CRLH leaky wave antenna of resonance type, the radiation angle θ can be evaluated from the expression of $\sin\theta=\beta_{NR}/\beta_0$ (See, for example, Non-Patent Document 1). In this case, β_0 denotes a phase constant in vacuum. Moreover, the nonreciprocal phase shift amount β_{NR} is the average value of the phase constants β_p and β_m with respect to the two propagation directions, through which the electromagnetic power may flow in a manner similar to that of the Equation (6), and represents the magnitude of nonreciprocity of the phase constant β. In this case, the variation Δθ of the radiation angle θ due to a change in the operating angular frequency ω by Δω from the center angular frequency ω_C is approximately given by the following equation in Non-Patent Document 1:

$$\Delta\theta(\Delta\omega) = \frac{\Delta\omega}{\sqrt{\beta_0^2-\beta_{NRC}^2}}\left(\frac{d\beta_{NR}}{d\omega}\bigg|_{\omega=\omega_C} - \frac{\beta_{NRC}}{\omega_C}\right). \tag{10}$$

Therefore, in order to prevent the beam squint from occurring in the vicinity of the center angular frequency ω_C in the nonreciprocal CRLH leaky wave antenna of resonance type having the nonreciprocal transmission line apparatus **70**E, it is required that the nonreciprocal phase shift amount β_{NR} is strictly proportional to the operating angular frequency co in the vicinity of the center angular frequency ω_C.

Next, an approximate expression of the nonreciprocal phase shift amount β_{NR} in the configuration of the nonreciprocal transmission line apparatus **70**E of FIG. **13**A is derived, and the conditions of the stub conductors **13**A and **13**B for substantially preventing the occurrence of the beam squint in the leaky wave antenna of resonance type using the nonreciprocal transmission line apparatus **70**E are derived by an eigenmode analysis.

In the present embodiment, the nonreciprocal transmission line apparatus **70**E is analyzed by combining the electromagnetic analysis with transmission line models. Referring to FIG. **13**A, the nonreciprocal transmission line apparatus **70**E is handled by being separated into a nonreciprocal line section (nonreciprocal section: NRS) having an electrical length L_{NR} in the Y-axis direction and a reciprocal line section (Reciprocal Section: RS) along the propagation direction (which is the direction along the Y axis) of electromagnetic waves in a manner similar to that of Non-Patent Document 3. Referring to FIG. **13**A, one pair of line sections NR and NRS becomes a T-type unit cell **60**E of a period length p. Further, the lumped element capacitors each having a capacitance $2C_{se}$ are inserted in the series branch on both sides of the unit cells **60**E connected in cascade.

FIG. **14** is a longitudinal sectional view of the ferrite square bar **15**A in the nonreciprocal line section NRS of FIG. **13**A. Referring to FIG. **14**, since the stub conductors **13**A and **13**B are provided between the ports P**1** and P**2** for the microstrip line **12**E in the nonreciprocal line section NRS, the boundary conditions at the boundaries on the −X side and the +X side of the microstrip line **12**E are expressed by using mutually different equivalent admittances Y_1 and Y_2. In this case, the admittances Y_1 and Y_2 are given respectively by the stub conductors **13**A and **13**B configured of short-circuit-terminated or open-terminated limited-length microstrip line. On the other hand, in the reciprocal line section RS, a stub conductor is provided neither in the −X direction nor the +X direction for the microstrip line **12**E, in which the ferrite square bar **15**A is embedded. Therefore, the boundary conditions at each of the boundaries on the −X side and the +X side of the microstrip line **12**E become a magnetic wall (whose impedance is infinite).

If the magnetic wall type boundary conditions are applied to the reciprocal line section RS, this leads to the edge guide mode simple dispersion relation described in Non-Patent Document 2.

On the other hand, by the eigenmode analysis proposed in Non-Patent Document 3, the dispersion relation to the nonreciprocal line section NRS is given in a manner similar to that of the following equation:

$$j\cot(wk_x) = \frac{\frac{\gamma^2}{(\omega/c)} + \mu\left(\tilde{Y}_1\tilde{Y}_2\frac{\mu^2-\mu_a^2}{\mu} + \varepsilon_r\right)\left(\frac{\omega}{c}\right)}{\mu k_x(\tilde{Y}_1+\tilde{Y}_2)} + \frac{\gamma\mu_a(\tilde{Y}_1-\tilde{Y}_2)}{\mu k_x(\tilde{Y}_1+\tilde{Y}_2)}. \tag{11}$$

It is noted that ω denotes an operating angular frequency, w is a width of the ferrite square bar **15**A, c denotes a velocity of light in vacuum, and ϵ_r denotes a relative dielectric constant of the ferrite square bar **15**A. The physical amount μ and μ_a denote a diagonal component and a non-diagonal component of the Polder relative permeability tensor:

$$\hat{\mu}_r = \begin{bmatrix} \mu & j\mu_a & 0 \\ -j\mu_a & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

of the ferrite square bar **15**A magnetized in the Z-axis positive direction.

Moreover,

$$\tilde{Y}_1 = Y_1\sqrt{\mu_0/\epsilon_0},\ \tilde{Y}_2 = Y_2\sqrt{\mu_0/\epsilon_0},$$

where μ_0 is a permeability in vacuum, and ϵ_0 is a dielectric constant in vacuum. Further, in the Equation (11), k_x that means a wave number in the transverse direction is given by the following equation:

$$k_x^2 = \gamma^2 + (\mu^2-\mu_a^2)\epsilon_r\omega^2/(\mu c^2).$$

Moreover, a complex propagation constant γ can be written as $\gamma=\alpha+j\beta$ by using a decay constant α and a phase constant β.

Regarding the macroscopic characteristics of the reciprocal line section RS and the nonreciprocal line section NRS, the characteristic impedance is estimated from the electromagnetic field distribution as a ratio of integral value of a pointing vector in a cross section to a surface current along the microstrip line **12**E. A relation between an electric field component E_Z of electromagnetic waves and magnetic field components H_X and H_Y can be obtained from the Maxwell equation. If there is no transmission loss, the characteristic impedance is reciprocal.

Next, an analysis of the eigenmode of propagation along the nonreciprocal transmission line apparatus **70**E is performed. The features of the structure of the nonreciprocal transmission line apparatus **70**E can be obtained by an ABCD matrix F_{UC} with respect to the unit cell **60**E. It is noted that the ABCD matrix F_{UC} with respect to the unit cell **60**E is expressed as $F_{UC}=F_{2C}F_{RS}F_{NRS}F_{RS}F_{2C}$ as a product of a matrix F_{RS} to the reciprocal line section RS, a matrix F_{NRS} to the nonreciprocal line section NRS, and a matrix F_{2C} to the capacitor of the capacitance $2C_{se}$. In this case, if periodic boundary conditions are applied to the traveling direction for the matrix F_{UC}, the dispersion relation is obtained by the following equation:

$$\det[F_{UC} - \hat{I}\exp(\gamma_{MM}p)] = 0,$$

where γ_{MM} represents a complex propagation constant of the mode of propagation along the periodic structure.

This equation can be formulated by using a magnitude of the nonreciprocal phase shift amount β_{NR} in the nonreciprocal line section NRS. In concrete, the nonreciprocal phase shift amount in the nonreciprocal line section NRS can be approximately expressed by a perturbation method on the assumption that μ_a has a small value. By applying the perturbation method to the dispersion relation of the nonreciprocal CRLH metamaterial, the magnitude of the nonreciprocal phase shift amount β_{NR} is given by the following equation:

$$\beta_{NR} = \frac{(\omega_M/c)(\tilde{Y}_2-\tilde{Y}_1)}{w\left(\frac{\omega}{c}\right)\frac{(\tilde{Y}_2+\tilde{Y}_1)}{2} - 2j}\frac{L_{NR}}{p}. \tag{12}$$

It is noted that ω_M is $(|g|\mu_0 M_S)$, and g denotes a gyromagnetic ratio. As apparent from the Equation (12), the nonreciprocity of the structure of the nonreciprocal transmission line apparatus **70**E is caused by (a) the asymmetry of the structure expressed by the following:

$$(\tilde{Y}_2-\tilde{Y}_1)$$

and (b) $\omega_M=|g|\mu_0 M_S$ that means the magnitude of the magnetization of the ferrite square bar **15**A. On the other hand, in the Equation (12), the term of:

$$(\tilde{Y}_2+\tilde{Y}_1)$$

represents the sum total of the admittances Y_1 and Y_2 of the two stub conductors **13**A and **13**B (See Non-Patent Document 4). The imaginary part of the total admittance of the inductive stub having a negative dielectric constant assumes a negative value. In the lossless case, the nonreciprocity appears only in the phase constant, the nonreciprocity appears only in the phase constant as pointed by, for example, Non-Patent Document 3.

FIG. **15** is a perspective view showing a configuration of a nonreciprocal transmission line apparatus **700** according to a comparative example. The nonreciprocal transmission line apparatus **700** of FIG. **15** is different from the nonreciprocal transmission line apparatus **70**E of the present embodiment such that unit cells **60**G are provided in place of the unit cells **60**E. In this case, the unit cells **600** is different from the unit cells **60**E such that the stub conductor **13**A is not provided, and the stub conductor **13**B is provided only on the +X side of the strip conductor **12**. Consequently, the stub conductors **13**B are periodically inserted only on the +X side of the microstrip line **12**E, and such propagation characteristics that the dielectric constant becomes negative are obtained. In Non-Patent Document 3, the characteristics of the nonreciprocal transmission line apparatus **700** are analyzed in a simple case where such propagation characteristics that the dielectric constant becomes negative are given.

FIG. **16** is a graph showing dispersion curves of the nonreciprocal transmission line apparatus **70**G of FIG. **15**, and showing simulation calculated values of the frequency characteristics of the nonreciprocal phase shift amount β_{NR}. Moreover, FIG. **17** is a graph showing dispersion curves of the nonreciprocal transmission line apparatus **70**E of FIG. **13**A, and showing simulation calculated values of the frequency characteristics of the nonreciprocal phase shift amount β_{NR}. The aforementioned Equation (12) represents that the nonreciprocal phase shift amount β_{NR} is approximately inversely proportional to the operating angular frequency ω in the nonreciprocal transmission line apparatus **70**G of FIG. **15**, in which the stub conductor is inserted only on one side of the microstrip line **12**E (See FIG. **16**). On the other hand, if the stub conductors **13**A and **13**B are inserted on both sides of the microstrip line **12**E in a manner similar to that of the nonreciprocal transmission line apparatus **70**E of the present embodiment of FIG. **13**A, the nonreciprocal phase shift amount β_{NR} becomes not inversely proportional to the operating angular frequency ω (See FIG. **17**).

Moreover, as shown in FIG. **16**, in the nonreciprocal transmission line apparatus **70**G of FIG. **15**, in which the stub conductor **13**B is inserted only on one side of the microstrip line **12**E, a first derivative $d\beta_{NR}(\omega)/d\omega$ relevant to the operating angular frequency ω of the nonreciprocal phase shift amount β_{NR} becomes $d\beta_{NR}(\omega)/d\omega<0$ (See Non-Patent Documents 1, 3 and 4).

On the other hand, as shown in FIG. **17**, in the nonreciprocal transmission line apparatus **70**E of FIG. **13**A, in which the stub conductors **13**A and **13**B are inserted on both sides of the microstrip line **12**E, the sign of the first derivative $d\beta_{NR}(\omega)/d\omega$ relevant to the operating angular frequency ω of the nonreciprocal phase shift amount β_{NR} is inverted when the nonreciprocal phase shift amount β_{NR} becomes zero at a predetermined operating angular frequency ω_Z longer than the center angular frequency ω_C, and this leads to $d\beta_{NR}(\omega)/d\omega>0$. Consequently, it can be understood that the nonreciprocal transmission line apparatus **70**E can be designed so that any beam squint does not substantially occur since the nonreciprocal phase shift amount β_{NR} is substantially proportional to the operating angular frequency ω in the vicinity of the center angular frequency ω_C.

In the leaky wave antenna of resonance type using the nonreciprocal transmission line apparatus **70**E, the present embodiment utilizes the fact that the admittances Y_1 and Y_2 change in accordance with the frequency in order to prevent the occurrence of the beam squint that the beam angle θ changes in accordance with the operating frequency. In general, the admittances $Y_1(\omega)$ and $Y_2(\omega)$ can be expressed by using the relational expression of the input impedance in the finite length microstrip line, in which the load impedance is connected to a transmission line terminal. In general, the input admittance contains a cotangent function or a tangent function when the transmission line terminal end is short-circuited or opened, and therefore, the input admittance has a singular point or a significant point at a predetermined frequency, and exhibits discontinuity.

Referring to the Equation (12), the nonreciprocal phase shift amount β_{NR} becomes zero when

$$\tilde{Y}_2-\tilde{Y}_1=0$$

i.e., when $Y_1=Y_2$, and a comparatively large nonreciprocal phase shift characteristic can also be obtained at a further operating angular frequency ω. From the characteristics of the trigonometric function owned by the admittances Y_1 and Y_2 of the inserted stub conductors **13**A and **13**B, such conditions of the admittances Y_1 and Y_2 can be found that the aforementioned beam squint becomes zero between two singular points (frequencies) at which

$$\tilde{Y}_1(\omega) \text{ or } \tilde{Y}_2$$

becomes discontinuous, i.e., the conditions of the electrical lengths La and Lb.

FIG. **19** is a graph showing dispersion curves of the nonreciprocal transmission line apparatus **70**E of FIG. **13**A, showing simulation calculated values of the frequency characteristics of the nonreciprocal phase shift amount β_{NR}, and showing experimental values when the nonreciprocal transmission line apparatus **70**E of FIG. **13**A is formed in a manner similar to that of FIG. **18** (described later). In FIG. **19** are shown the simulation calculated values of the phase constant β_p when the transmission power is in the forward direction (positive direction), the phase constant $-\beta_m$ when it is in the backward direction (negative direction), and the nonreciprocal phase shift amount β_{NR} calculated on the basis of the phase constants β_p and $-\beta_m$. The finite element method was used for the simulations. Further, the theoretical value of the nonreciprocal phase shift amount β_{NRZ} when any beam squint does not occur at all and the phase constant β_0 in vacuum are additionally shown. The center angular frequency ω_C of the antenna using the nonreciprocal transmission line apparatus **70**E is defined by the operating angular frequency at the intersection of two dispersion curves in the left-handed mode and the right-handed mode, and the center angular frequency ω_C can be confirmed to be 6.8 GHz in FIG. **19**. Moreover, it can be understood that the nonreciprocal phase shift amount β_{NR} comes close to the nonreciprocal phase shift amount β_{NRZ} in the ideal case where any beam squint does not occur at all in the vicinity of the center angular frequency ω_C, and any beam squint does not substantially occur.

FIG. **18** is a plan view showing a concrete configuration of the nonreciprocal transmission line apparatus **70**E of FIG. **13**A. As shown in FIG. **19**, an experimental model of the nonreciprocal transmission line apparatus **70**E was manufactured for trial purposes. In the nonreciprocal transmission line apparatus **70**E of FIG. **19**, a ferrite square bar **15**A made of yttrium iron garnet (YIG) having a sectional size of 0.8 mm×0.8 mm is embedded under the microstrip line **12**E. Moreover, the stub conductors **13**A and **13**B were formed on the dielectric substrate **10** of Rexolite (registered trademark) 2200. Further, the electrical length La of the stub conductor **13**A was set to 25 mm, and the electrical length Lb of the stub conductor **13**B was set to 2.5 mm. The width of each of the stub conductors **13**A and **13**B was set to 1 mm, and the period length "p" of the unit cells **60**E was set to 3 mm. The capacitance of the capacitors Cse was set to 0.5 pF so that dispersion characteristics having no band-gap between the right-handed mode and the left-handed mode result. Moreover, as shown in FIG. **18**, a grounding conductor **18** having a width thinner than the width of the stub conductor **13**A was formed between adjacent stubs **13**A in order to suppress the capacitive coupling between the adjacent stub conductors **13**A.

The phase constants β_p and $-\beta_m$ and the nonreciprocal phase shift amount β_{NR} at the time of manufacturing the nonreciprocal transmission line apparatus **70**E of FIG. **13**A in a manner similar to that of FIG. **18** for trial purposes are shown in FIG. **19**. As shown in FIG. **19**, the experimental values coincide well with the respective simulation calculated values. In particular, in the band from 5.3 GHz to 7.7 GHz, the dispersion characteristics of the nonreciprocal phase shift amount β_{NR} coincide well with the nonreciprocal phase shift amount β_{NRZ} in the ideal case where any beam squint does not occur in the pseudo traveling wave resonator antenna. That is, according to the nonreciprocal transmission line apparatus **70**E of the present embodiment, such an antenna apparatus of resonance type that any beam squint does not substantially occur in the vicinity of the center angular frequency ω_C of the operation band can be achieved.

As described above, it has been described that the occurrence of the beam squint can be substantially prevented in the antenna apparatus using the nonreciprocal transmission line apparatus **70**E by analyzing the magnitudes of the phase constants β_p and $-\beta_m$ in the nonreciprocal transmission line apparatus **70**E. Moreover, when the nonreciprocal transmission line apparatus **70**E was manufactured for trial purposes and the transmission characteristics were measured, it was confirmed that the experimental values coincided well with the simulation calculated values. Therefore, if the nonreciprocal transmission line apparatus **70**E is applied to the leaky wave antenna of resonance type, a beam scanning antenna apparatus can be achieved, in which the beam squint does not substantially occur.

MODIFIED EMBODIMENTS

FIG. **20**A is a perspective view showing a configuration of a nonreciprocal transmission line apparatus **70**F according to a modified embodiment of the present invention. Referring to FIG. **20**A, the nonreciprocal transmission line apparatus **70**F is different from the nonreciprocal transmission line apparatus **70**E of the embodiment such that unit cells **60**F are provided in place of the unit cells **60**E. Moreover, the unit cells **60**F is different from the unit cells **60**E only such that capacitors Csh of chip capacitors are further provided. Hereinafter, only the different points from those of the embodiment are described. Referring to FIG. **20**A, one electrode of each capacitor Csh is connected to a predetermined connection point of the longer stub conductor **13**A of the stub conductors **13**A and **13**B, while the other electrode of the capacitor Csh is connected to the grounding conductor **11** via a via conductor **19**.

As described in the embodiments, the admittances Y_1 and Y_2 of the stub conductors **13**A and **13**B give frequency dependence to the boundary conditions on the side surface on the −X side and the side surface on the +X side of the microstrip line **12**E. In this case, it is possible to make $\beta_{NR}=0$ at a predetermined operating angular frequency ω_Z lower than the center angular frequency ω_C by using the stub conductors **13**A and **13**B having admittances Y_1 and Y_2, respectively, which are different from each other, and are inserted on both sides of the microstrip line **12**E. On the other hand, it is possible to secure large nonreciprocity at a frequency higher than the center angular frequency ω_C and to further make the nonreciprocal phase shift amount $\beta_{NR}(\omega)$ an increasing function (See FIG. **17**).

In FIG. **20**A, the equivalent admittance Y_1 of the grounded longer stub conductor **13**A is expressed by the following equation, using the characteristic impedance Z_{st} of the microstrip line including the stub conductor **13**A, the effective dielectric constant ϵ_{st}, and the electrical length La of the stub conductor **13**A:

$$Y_1=-z_{st}^{-1}\cot(La\sqrt{\epsilon_{st}}\omega/c).$$

By combining the grounded stub conductor **13**A with the grounded stub conductor **13**B, the condition of $\beta_{NR}=0$ can be approximately satisfied at the operating angular frequency ω_Z lower than the center angular frequency ω_C. In this case, the fact that the aforementioned condition is satisfied at the angular frequency that is not so much separated from the angular frequency $\omega=\pi c/La\sqrt{\epsilon_{st}}$ can be analogized by the function form of the admittance Y_1 of the stub conductor **13**A.

In this case, the fact that the nonreciprocal phase shift amount $\beta_{NR}(\omega)$ is the increasing function of the operating angular frequency ω does not mean that the beam squint can be easily made to disappear but sometimes deteriorates the maximum radiation beam angle as described in the embodiment. In the present modified embodiment, the admittance Y_1 of the longer stub conductor **13**A is adjusted by providing an additional capacitor Csh. With this arrangement, the controllability of the nonreciprocal phase shift amount $\beta_{NR}(\omega)$ can be improved as compared with the embodiment. With this arrangement, the nonreciprocal transmission line apparatus **70**F can be designed so that $\beta_{NR}(\omega)\propto\omega$ substantially results in the vicinity of the center angular frequency ω_C when the value of the nonreciprocal phase shift amount $\beta_{NR}(\omega)$ is larger. Therefore, the occurrence of the beam squint can easily be suppressed as compared with the embodiment.

It is acceptable to use a ferrite square bar having no spontaneous magnetization in place of the ferrite square bar **15**A having spontaneous magnetization and apply a magnetic field by the external magnetic field generator **80** of FIG. **20**B.

FIG. **21** is a graph showing dispersion curves of the nonreciprocal transmission line apparatus **70**F of FIG. **20**A, and showing simulation calculated values of the frequency characteristics of the nonreciprocal phase shift amount β_{NR}, and FIG. **22** is an enlarged view of FIG. **21**. The finite element method was used for the simulations. A ferrite square bar **15**A made of yttrium iron garnet (YIG) having a sectional size of 0.8 mm×0.8 mm was embedded under the microstrip line **12**E. Moreover, the electrical length La of the stub conductor **13**A was set to 25.5 mm so that the nonreciprocal phase shift amount β_{NR} becomes zero at 5 GHz, which is lower than the frequency corresponding to the center angular frequency ω_C, the electrical length Lb of the stub conductor **13**B was set to 1.3 mm, and the width of the stub conductors **13**A and **13**B was set to 1 mm. Further, the capacitance of the capacitor Csh was set to 0.4 pF so that the beam squint does not substantially occur, and the capacitance of the capacitor Cse was set to 0.65 pF so to obtain a dispersion characteristic having no band-gap between the right-handed mode and the left-handed mode. Further, the relative dielectric constant of the dielectric substrate **10** was set to 2.6.

As described above, the electrical lengths La and Lb of the stub conductors **13**A and **13**B are set to 25.5 mm and 1.3 mm, respectively, and the nonreciprocal transmission line apparatus **70**F has a structure of a strong asymmetry with respect to the microstrip line **12**E. As shown in FIGS. **21** and **22**, the operating frequency $\omega_C/(2\pi)$ at the intersection of two dispersion curves became 6.0 GHz. Moreover, the nonreciprocal phase shift amount β_{NR} is proportional to the frequency in the vicinity of the operating frequency $\omega_C/(2\pi)$ and comes close to the nonreciprocal phase shift amount β_{NRZ} when the beam squint does not occur at all. Further, if the magnitude of the obtained nonreciprocal phase shift amount β_{NRZ} is converted into the radiation beam angle of the antenna apparatus designed on the basis of this structure, it has been confirmed that beam scanning could be performed up to an angle of 28 degrees at maximum.

As described in detail above, the nonreciprocal transmission line apparatuses **70**E and **70**F are configured by connecting in cascade the unit cells **60**E or **60**F between the ports P**1** and P**2**, where the propagation constant in the forward direction and the propagation constant in the backward direction are different from each other. In this case, each of the unit cells **60**E and **60**F has a microwave transmission line section, a capacitor Cse that is the series branch circuit equivalently containing a capacitance element, and first and second parallel branch circuits that are each provided branched from the microwave transmission line section and equivalently containing an inductive element. Moreover, the transmission line section has spontaneous magnetization so as to have gyro anisotropy by being magnetized in a direction different from the propagation direction of microwaves or is magnetized by external magnetization. Further, the first parallel branch circuit is the stub conductor **13**A having an electrical length La, and the second parallel branch circuit is the stub conductor **13**B having an electrical length Lb shorter than the electrical length La.

Further, when the phase constant in the first mode of propagation in the forward direction is assumed to be β_p, and the phase constant in the second mode of propagation in the backward direction is assumed to be β_m, the electrical lengths La and Lb are characterized by being set so that the function of the nonreciprocal phase shift amount $\beta_{NR}=(\beta_p-\beta_m)/2$ with respect to the operating angular frequency comes close to the function β_{NRZ} of the nonreciprocal phase shift amount β_{NR} with respect to the operating angular frequency, when the beam squint of such a phenomenon that the radiation direction of electromagnetic waves radiated from the nonreciprocal transmission line apparatus changes in accordance with the frequency does not occur in the vicinity of the intersection of the first dispersion curve that exhibits the relation between the phase constant β_p and the operating angular frequency and the second dispersion curve that exhibits the relation between the phase constant β_m and the operating angular frequency.

More concretely, in the antenna apparatus having the nonreciprocal transmission line apparatus **70**E or **70**F, the nonreciprocal phase shift amount β_{NR} is required to be proportional to the operating angular frequency ω in the vicinity of the center angular frequency ω_C in order to substantially prevent occurrence of the beam squint in the vicinity of the center angular frequency ω_C that is the operating angular frequency at the intersection of the aforementioned two dispersion curves. That is, the following equation is required to substantially hold in the vicinity of the center angular frequency ω_C:

$$\frac{\beta_{NR}}{\beta_0} = \text{constant.}$$

Moreover, in order to make this equation hold, the electrical length La of the stub conductor **13**A and the electrical length Lb of the stub conductor **13**B are set so that the admittance Y_1 of the stub conductor **13**A and the admittance Y_2 of the stub conductor **13**B satisfy the following first and second conditions.

The first condition: The nonreciprocal phase shift amount β_{NR} assumes the value of zero at the predetermined operating angular frequency ω_Z, that is in the vicinity of the center angular frequency ω_C of the antenna apparatus having the nonreciprocal transmission line apparatus **70**F and is lower than the center angular frequency ω_C. That is, the admittances Y_1 and Y_2 of the stub conductors **13**A and **13**B inserted on both sides of the microstrip line **12**E satisfy $Y_1=Y_2$ at the operating angular frequency ω_Z (See Equation (12)).

The second condition: Both of the admittances Y_1 and Y_2 must be inductive (inductance) at the aforementioned operating angular frequency ω_Z. That is, since the stub conductors **13**A and **13**B must be inductive stubs having a negative dielectric constant at the operating angular frequency ω_Z, $Im(Y_1)=Im(Y_2)<0$.

In the nonreciprocal transmission line apparatuses **70**E and **70**F, although one end of the stub conductor **13**A is grounded, it may be opened. The inventor and others of the present application discovered that the electrical lengths La and Lb (La>Lb) should be set to satisfy the following additional third and fourth conditions depending on whether one end of the stub conductor **13**A is grounded (short-circuit stub) or opened (open stub). It is noted that λ is a guide wavelength in each of the following conditions.

The first case (in the case where the stub conductor **13**A is a short-circuit stub):

The third condition: The stub conductor **13**A is a short-circuit stub satisfying $La>\lambda/2$.

The fourth condition: The stub conductor **13**B is a short-circuit stub that satisfying $Lb<\lambda/4$.

The second case (in the case where the stub conductor **13**A is an open stub):

The third condition: The stub conductor **13**A is an open stub satisfying $La>\lambda/4$.

The fourth condition: The stub conductor **13**B is a short-circuit stub satisfying $Lb<\lambda/4$.

As described above, the nonreciprocal phase shift amount β_{NR} can be increased by additionally connecting a lumped element capacitance such as a chip capacitor to the predetermined connection point of the stub conductor **13**A in the first and second cases. Therefore, the occurrence of the beam squint can be substantially suppressed even if the radiation beam angle θ becomes relatively large.

Next, the admittances Y_1 and Y_2 in the aforementioned second case are considered. FIG. **23** is a plan view schematically showing a configuration of a nonreciprocal transmission line apparatus **70**F when the stub conductor **13**A of FIG. **20**A is an open stub. Moreover, FIG. **24** is a graph showing an operating angular frequency dependence of the admittances Y_1 and Y_2 in the nonreciprocal transmission line apparatus **70**F of FIG. **23**, and showing frequency dependence of the nonreciprocal phase shift amount β_{NR}.

Referring to FIG. **23**, each of the stub conductors **13**A and **13**B operates as an inductive stub conductor. Moreover, as described above, the electrical length La is set to satisfy La>λ/4, and the electrical length Lb is set to satisfy Lb<λ/4. As shown in FIG. **24**, when the stub conductor **13**A is an open stub, the admittance Y_1 becomes a tangent function (tan) relevant to the operating angular frequency ω. Moreover, when the stub conductor **13**B is a short-circuit stub, the admittance Y_2 becomes a cotangent function (cot) relevant to the operating angular frequency ω. Referring to FIG. **24**, the nonreciprocal phase shift amount β_{NR} becomes zero at the operating angular frequency ω_Z that is in the vicinity of the center angular frequency ω_C and lower than the center angular frequency ω_C. As described above, at this operating angular frequency ω_Z, the admittances Y_1 and Y_2 are inductive (inductance), and the imaginary part of each of the admittances Y_1 and Y_2 assumes a negative value.

As indicated by the aforementioned Equation (12), the nonreciprocal phase shift amount β_{NR} has a factor proportional to (Y_2-Y_1), and this means that the frequency dependence of the nonreciprocal phase shift amount β_{NR} is influenced by the frequency dependence of (Y_2-Y_1). Referring to FIG. **24**, the admittance Y_2 changes very gently with respect to the operating angular frequency and has no singular point. On the other hand, the admittance Y_1 changes with respect to the operating angular frequency more suddenly than the admittance Y_2 and has a plurality of periodic singular points. Therefore, the operating angular frequency ω_Z at which the nonreciprocal phase shift amount β_{NR} becomes zero is determined substantially by the operating angular frequency corresponding to the singular points of the admittance Y_1. Moreover, the admittance Y_2, which changes more gently than the admittance Y_1, merely operates to increase the value of the nonreciprocal phase shift amount β_{NR} and to shift it rightward in FIG. **2** in the calculation of the nonreciprocal phase shift amount β_{NR} (i.e., calculation of (Y_2-Y_1)).

Referring to FIG. **24**, the gradient $d\beta_{NR}/d\omega$ of the nonreciprocal phase shift amount β_{NR} relevant to the operating angular frequency ω is determined by the operating angular frequency dependence of (Y_2-Y_1), and the maximum radiation beam angle is also determined by the frequency dependence of this nonreciprocal phase shift amount β_{NR}. In concrete, the maximum radiation beam angle becomes larger as the value of $d\beta_{NR}/d\omega$ is larger. Referring to FIG. **23**, in the nonreciprocal transmission line apparatus **70**E, the capacitor Csh was connected to the predetermined connection point of the longer stub conductor **13**A. With this arrangement, in FIG. **24**, the gradient relevant to the operating angular frequency ω of (Y_2-Y_1) increases, and $d\beta_{NR}/d\omega$ can be consequently increased. Therefore, the maximum radiation beam angle can be greatly improved while maintaining the state, in which the beam squint does not substantially occur as compared with the nonreciprocal transmission line apparatus **70**E with no capacitor Csh.

In order to confirm the operation of the pseudo traveling wave resonator antenna using the nonreciprocal transmission line apparatus **70**E in the aforementioned second case, a simulation was performed by using the ANSYS HFSS ver **13** of high-frequency three-dimensional electromagnetic analysis software.

FIG. **25** is a plan view showing a concrete configuration used for the simulation of the nonreciprocal transmission line apparatus **70**F of FIG. **23**, and FIG. **26** is a perspective view of the nonreciprocal transmission line apparatus **70**F of FIG. **25**. In FIG. **25**, the width of the strip conductor **12** was set to 0.8 mm, the electrical length La of the stub conductor **13**A was set to 14 mm, and the electrical length Lb of the stub conductor **13**B was set to 1.7 mm. The width of each of the stub conductors **13**A and **13**B was set to 1 mm, and a distance between the strip conductor **12** and the capacitor Csh was set to 2.65 mm. Moreover, the period length p was set to 3 mm, and the periodic number was set to 15. The capacitance of the capacitor Cse was set to 0.4 pF, and the capacitance of the capacitor Csh was set to 0.1 pF. Referring to FIG. **26**, the stub conductor **13**A is an open stub, and the stub conductor **13**B is a short-circuit stub.

Further, referring to FIG. **25**, a reflector R**1** was connected to the port P**1**, a reflector R**2** was connected to the port P**2**, and a feed line F was connected to the reflector R**1**. In this case, the widths in the X-axis direction of the reflectors R**1** and R**2** were each set to 4.5 mm. Moreover, the width in the Y-axis direction of the reflector R**1** was set to 19.2 mm that is about three-fourth of the guide wavelength, and the width in the Y-axis direction of the reflector R**2** was set to 6.25 mm that is about one-fourth of the guide wavelength. Further, the sectional size of the ferrite square bar **15**A was set to 0.8 mm×0.8 mm. It is noted that the saturation magnetization was made to be $\mu_0 M_S$=160 mT. Moreover, in order to suppress capacitive coupling between adjacent stub conductors **13**A, a grounding conductor **50** having a width thinner than the width of each of the stub conductors **13**A was formed between stub conductors **13**A adjacent to each other.

FIG. **27** is a graph showing dispersion curves of the nonreciprocal transmission line apparatus **70**F of FIG. **25**, and showing simulation-calculated values of the frequency characteristics of the nonreciprocal phase shift amount β_{NR}. As shown in FIG. **27**, it can be understood that the simulation-calculated values of the nonreciprocal phase shift amount β_{NR} coincide well with the nonreciprocal phase shift amount β_{NRZ} in the ideal case where the beam squint does not occur at all.

FIG. **28** is a graph showing radiation characteristics of the nonreciprocal transmission line apparatus **70**F of FIG. **25**. FIG. **28** shows a case where the operating frequency is 7.35 GHz. It can be confirmed from FIG. **28** that the radiation angle θ of the main beam is inclined by 19 degrees from 0 degrees.

FIG. **29** is a graph showing frequency characteristics of a radiation angle θ of the nonreciprocal transmission line apparatus **70**F of FIG. **25**, and FIG. **30** is a graph showing frequency characteristics of a radiant gain of the nonreciprocal transmission line apparatus **70**F of FIG. **25**. It can be confirmed from FIG. **29** that the radiation angle θ is almost constant over for a frequency band from 7.20 GHz to 7.55 GHz. Therefore, it can be understood that an operating ratio band equal to or larger than 4% where the beam squint does not substantially occur is achieved. That is, according to the present embodiment, the operating ratio band where the beam squint does not substantially occur could be greatly improved as compared with the operating ratio band of 2% in the case where the stub conductor was provided only on one side of the strip conductor of the microstrip line **12**E (See Non-Patent Document 1).

FIG. **31**A is a perspective view showing a configuration of a pseudo traveling wave resonant antenna apparatus that uses the nonreciprocal transmission line apparatus **70**F of FIG. **25**. In the pseudo traveling wave resonant antenna apparatus of FIG. **31**A, the lengths of the two reflectors R**1** and R**2** are adjusted so that short-circuit is achieved at each of the ports P**1** and P**2** when viewed from the nonreciprocal transmission line apparatus **70**F. The reflector R**2** on the side connected to the feed line F has such a structure that is longer by half the wavelength in order to secure the connecting portion of the feed line F as compared with the reflector R**2** on the non-connected side, and unnecessary radiation is consequently caused. For the suppression of this unnecessary radiation, a shield structure by a metallic shield plate **90** is adopted as the reflector R**2**.

FIG. **31**B is a graph of numerical calculation results of the pseudo traveling wave resonant antenna apparatus of FIG. **31**A, showing frequency characteristics of a reflection coefficient S_{11} when the pseudo traveling wave resonant antenna apparatus is viewed from the feed line F. The graph of FIG. **31**B means that the antenna apparatus resonates at three frequencies at which the reflection is small, and electromagnetic waves are consequently radiated from this antenna apparatus. Regarding the resonance in the 6.5 GHz and 7.4 GHz bands of the three resonance frequencies, half-wavelength resonance occurs inside the CRLH line. In contrast to this, the resonance condition at 6.9 GHz operates as a pseudo traveling wave resonance to which attention is paid in the present embodiment.

FIG. **31**C is a graph of numerical calculation results of the pseudo traveling wave resonant antenna apparatus of FIG. **31**A, showing a magnetic field distribution along a longitudinal direction of the nonreciprocal transmission line apparatus **70**F and a normalized amplitude of an electric field distribution. As apparent from FIG. **31**, such a resonance that the magnetic field is ideally dominant results, and the electric field component becomes small in the case of the both-end short-circuited resonator.

FIG. **31**D is a graph of numerical calculation results of the pseudo traveling wave resonant antenna apparatus of FIG. **31**A, showing a phase gradient of the magnetic field distribution along the longitudinal direction of the nonreciprocal transmission line apparatus **70**F. As apparent from FIG. **31**D, a phase change of about 70 degrees is confirmed with respect to a length of 30 mm in a portion of the nonreciprocal transmission line apparatus **70**F.

FIG. **31**E is a graph of numerical calculation results of the pseudo traveling wave resonant antenna apparatus of FIG. **31**A, showing frequency characteristics of a radiation beam angle in a broad side direction of the pseudo traveling wave resonant antenna apparatus. That is, FIG. **31**E plots a radiation beam angle from the pseudo traveling wave resonant antenna apparatus with respect to the broad side direction, which is used as a criterion, and exhibits the same plot as a function of the operating frequency. In the case where the magnetization is $4\pi M=-1600$ G, it is confirmed that the beam direction becomes almost constant within a range of a ratio band of 4% from 6.85 GHz to 7.15 GHz, and the beam squint is reduced. Further, it also exhibits the case where the magnitude of magnetization and the internal magnetic field is changed to $4\pi M=0$ G+1600 G. Although the effects of suppressing the beam squint deteriorates a little, a similar tendency is confirmed.

FIG. **31**F is a graph of numerical calculation results of the pseudo traveling wave resonant antenna apparatus of FIG. **31**A, showing a radiation pattern in a plane perpendicular to the longitudinal direction of the pseudo traveling wave resonant antenna apparatus. As apparent from FIG. **31**F, a radiation gain of 8 dBi is obtained with respect to an input signal at the operating frequency of 7 GHz in the case where the applied magnetic field $4\pi M=+1600$ G.

FIG. **32**A is a photograph showing a trial manufacture example of the pseudo traveling wave resonant antenna apparatus of FIG. **31**A, and FIG. **32**B is a graph of experimental results of the pseudo traveling wave resonant antenna apparatus related to the trial manufacture example of FIG. **32**A, showing frequency characteristics of the radiation beam angle in the broad side direction of the pseudo traveling wave resonant antenna apparatus. As apparent from FIG. **32**A, there are shown three cases where the externally applied magnetic field Hex=−1000, 0 and +1000 Oe. The band, in which the beam squint becomes strictly zero such that the radiation beam angle does not change due to the frequency, is smaller than that of the numerical calculation results shown in FIG. **31**E. However, the operation band, in which the beam squint is reduced, has been greatly improved as compared with the case of the pseudo traveling wave resonant structure having no beam squint suppression function manufactured for trial purposes in the past.

FIG. **32**C is a graph of experimental results of the pseudo traveling wave resonant antenna apparatus according to the trial manufacture example of FIG. **32**A, showing a radiation pattern in a plane perpendicular to the longitudinal direction of the pseudo traveling wave resonant antenna apparatus. In this case, there is shown a case where the operating frequency is 6.63 GHz and the externally applied magnetic field Hex=−1000 Oe. As apparent from FIG. **32**C, it can be understood that the beam is owned in a direction slightly rearward from the center in the longitudinal direction of the pseudo traveling wave resonant antenna apparatus.

It is noted that, in the nonreciprocal transmission line apparatus **70**A of the embodiment, the electrical lengths La and Lb of each of the stub conductors **13**A and **13**B may be set as described in the embodiments and the modified embodiments.

INDUSTRIAL UTILIZABILITY

According to the nonreciprocal transmission line apparatus and the antenna apparatus of the present invention, the function of the nonreciprocal phase shift amount $\beta_{NR}=(\beta_p-\beta_m)/2$ with respect to the operating angular frequency is configured so as to come close to the function of the nonreciprocal phase shift amount β_{NR} with respect to the operating angular frequency when the beam squint of such a phenomenon that the radiation direction of electromagnetic waves radiated from the nonreciprocal transmission line apparatus changes in accordance with the frequency does not occur. Therefore, the beam squint does not substantially occur in the vicinity of the center frequency of the operation band.

The nonreciprocal transmission line apparatuses **70**A to **70**F of the present invention are useful as devices and antenna apparatuses for signal transmission.

REFERENCE NUMERICALS

10: Dielectric substrate
11, **18**, **22**, **23**, **50**: Grounding conductor

12, 21, 24: Strip conductor
12A: Coplanar line
12E: Microstrip line
13A, 13B: Stub conductor
15: Ferrite plate
15A: Ferrite square bar
17A, 17B: Grounding conductor
60A to 60F: Unit cell
61, 62: Transmission line section
70A-60F: Nonreciprocai transmission line apparatus
80: External magnetic field generator
C, C1, C2, C60, Cse, Csh: Capacitor
P1, P2, P11, P12: Port

The invention claimed is:

1. A nonreciprocal transmission line apparatus configured by connecting in cascade at least one unit cell, each unit cell including:

(a) a microwave transmission line section;

(b) a series branch circuit equivalently including a capacitance element; and

(c) first and second parallel branch circuits provided branched from the transmission line section, each of the first and second parallel branch circuit equivalently including an inductive element between first and second ports,

wherein a propagation constant in a forward direction and a propagation constant in a backward direction of the nonreciprocal transmission line apparatus are different from each other,

wherein the transmission line section of each unit cell has spontaneous magnetization so as to have gyro anisotropy by being magnetized in a direction different from a propagation direction of microwaves or by being externally magnetized by an external magnetic field,

wherein the first parallel branch circuit is a first stub conductor having a first electrical length,

wherein the second parallel branch circuit is a second stub conductor having a second electrical length shorter than the first electrical length, and

wherein, when a phase constant in a first mode of propagation in the forward direction is β_p, and a phase constant in a second mode of propagation in the backward direction is β_m, the first and second electrical lengths are set so that a function of nonreciprocal phase shift amount $\beta_{NR}=(\beta_p-\beta_m)/2$ with respect to the operating angular frequency comes close to a function of nonreciprocal phase shift amount β_{NRZ} with respect to an operating angular frequency, when beam squint of such a phenomenon that a radiation direction of electromagnetic waves radiated from the nonreciprocal transmission line apparatus changes in accordance with frequency does not occur in the vicinity of an intersection of a dispersion curve representing a relation between the phase constant β_p and the operating angular frequency and a dispersion curve representing a relation between the phase constant β_m and the operating angular frequency.

2. The nonreciprocal transmission line apparatus as claimed in claim 1,

wherein the function is a function proportional to the operating angular frequency.

3. The nonreciprocal transmission line apparatus as claimed in claim 2,

wherein the first stub conductor has a first admittance,

wherein the second stub conductor has a second admittance, and

wherein the first and second electrical lengths are set such that:

(a) the first admittance substantially coincides with the second admittance at a predetermined operating angular frequency lower than the operating angular frequency at the intersection, and

(b) respective imaginary parts of the first and second admittances are negative at the predetermined operating angular frequency.

4. The nonreciprocal transmission line apparatus as claimed in claim 3,

wherein the first stub conductor is a short-circuit stub, and the first electrical length is set to be longer than one-half of a guide wavelength, and

wherein the second stub conductor is a short-circuit stub, and the second electrical length is set to be shorter than one-fourth of the guide wavelength.

5. The nonreciprocal transmission line apparatus as claimed in claim 3,

wherein the first stub conductor is an open stub, and the first electrical length is set to be longer than one-fourth of a guide wavelength, and

wherein the second stub conductor is a short-circuit stub, and the second electrical length is set to be shorter than one-fourth of the guide wavelength.

6. The nonreciprocal transmission line apparatus as claimed in claim 1, further comprising a grounding conductor provided between the first stub conductors, the grounding conductor providing a shield between the first stub conductors.

7. An antenna apparatus comprising a nonreciprocal transmission line apparatus configured by connecting in cascade at least one unit cell, each unit cell including:

(a) a microwave transmission line section;

(b) a series branch circuit equivalently including a capacitance element; and

(c) first and second parallel branch circuits provided branched from the transmission line section, each of the first and second parallel branch circuit equivalently including an inductive element between first and second ports,

wherein a propagation constant in a forward direction and a propagation constant in a backward direction of the nonreciprocal transmission line apparatus are different from each other,

wherein the transmission line section of each unit cell has spontaneous magnetization so as to have gyro anisotropy by being magnetized in a direction different from a propagation direction of microwaves or by being externally magnetized by an external magnetic field,

wherein the first parallel branch circuit is a first stub conductor having a first electrical length,

wherein the second parallel branch circuit is a second stub conductor having a second electrical length shorter than the first electrical length, and

wherein, when a phase constant in a first mode of propagation in the forward direction is β_p, and a phase constant in a second mode of propagation in the backward direction is β_m, the first and second electrical lengths are set so that a function of nonreciprocal phase shift amount $\beta_{NR}=(\beta_p-\beta_m)/2$ with respect to the operating angular frequency comes close to a function of nonreciprocal phase shift amount β_{NRZ} with respect to an operating angular frequency, when beam squint of such a phenomenon that a radiation direction of electromagnetic waves radiated from the nonreciprocal transmission line apparatus changes in accordance with frequency does not occur in the vicinity of an intersection of a dispersion curve representing a relation between the phase constant β_p and the operating angular frequency and a dispersion curve representing a relation between the phase constant β_m and the operating angular frequency.

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